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A CLOSED-LOOP SUPPLY CHAIN OPERATION DECISION UNDER LIFE CYCLE: ECOLOGICAL DESIGN, SERVICE DESIGN AND RECYCLING EFFORT PERSPECTIVES

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Abstract. The commercial, environmental and social value of closed-loop supply chain (CLSC) has been widely recognised in the literature. Enterprises are increasingly aware of the importance of product life cycle management; that is, enterprises conduct CLSC management of the production, use and recycling of products. Existing research lacks research on CLSC operation decision under product life cycle. This paper introduces ecological design, service design and recycling into a CLSC with the manufacturer, retailer and recycler. Stackelberg models considering different leadership structures and service design providers are constructed using game theory, and we use backward induction to solve the game in different cases. Results show that from the system-operating efficiency and total profits maximisation perspectives, the recycler-led is always the most effective. However, for the selection of the optimal service design provider, when the manufacturer (retailer) is the leader, the retailer (manufacturer) providing the service design should be the dominant strategy. When the recycler is the leader, the effect is the same no matter who provides the service design. Finally, we find an interesting conclusion that in the case of retailer provides service design, supply chain members do not always achieve the highest profits under their own leadership structure. The numerical analysis shows that when the consumer's preference for service design is greater than 6.3, the manufacturer can obtain greater profits under the recycler-led structure, and when consumer's preference for ecological design is greater than 7.1, the retailer can gain greater profits under the recycler-led structure.

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1. Introduction

Accompanying the current development of the global economy and the gradual increase in consumer product demand is a trend in the retirement of products. If these waste products (especially electrical products) cannot be treated scientifically, this will result in significant pollution of the environment [1]. A closed-loop supply chain (CLSC) management with a process of "production → recycling → remanufacturing" can effectively solve

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the above problems [2]. For one, CLSC can reduce environmental pollution caused by discarded waste products [3]. Moreover, the remanufacturing of waste products can save resources and realise the reuse of those resources [4]. In this context, enterprises are beginning to align with the CLSC management mode. For example, in 2022, Caterpillar's remanufacturing industry updated its global strategy to focus on supply chain management as a fourth key area, emphasising helping its supplier achieve remanufacturing. In addition, Brian Ed Wards, vice president of Caterpillar, also said that remanufacturing can save 85% of energy consumption, 85% of raw material consumption and 85% of water consumption. Therefore, the study of CLSC operation has certain theoretical and practical significance.

However, from the perspective of the life cycle process of production → use → recycling [5], recycling and remanufacturing can only reduce the environment pollution of waste products at the end of a product's life cycle; that is, it only can reduce the discarding of waste products and achieve cyclic utilization of waste products. To put it another way, it cannot reduce CO2e in the production process and cannot extend the product use time [6]. With the deepening of the sustainable development concept, the supply chain is exploring how to seek economic development while considering environmental protection and social welfare [7], that is, the CLSC needs to measure the sustainable development of the system from the three dimensions of economy, environment and society [8]. Therefore, in addition to considering the reuse of resources, the CLSC system also needs to incorporate the green concept and social welfare concept into each stage of the product life cycle [5,9]. Specifically, product life cycle management under the sustainable development should consider not only the recycling and reuse of products at the end of life but also the sustainability of products at the production stage and use stage [10], for example, ecological design (product production stage) and service design (product use stage).

(i) **Ecological design.** Under the concept of life cycle management and sustainable development, it is necessary to consider how to realise environmental protection in the production stage, which requires the manufacturing enterprise to implement ecological design for products [11]. Ecological design mainly refers to the enterprise achieving green production and reducing CO2e by establishing green factories, transforming factory facilities and optimising production processes [12]. For example, Gree Electric Appliance has built a zero-carbon industrial zone, reducing CO2e by 1443.08 tons each year, and reducing product energy consumption costs by 31.85%. Ecological design provides many benefits to the environment and also helps improve the enterprise's image and social influence [13]. In addition, although ecological design increases production costs, it does not necessarily bring economic losses to the enterprise [14]. Research demonstrates that increasingly more consumers are willing to pay a premium for green products, and an enterprise's ecological design has a market expansion effect and improves enterprise profits [15]. This further proves the positive effect of ecological design on economy, society and environment. Moreover, owing to the interaction among members of the supply chain, it is particularly important to study the ecological design of the manufacturing enterprise for the production, recycling and profit distribution of the CLSC system.

(ii) **Service design.** Service design refers to how, in the use stage of products, enterprises provide services for consumers through personnel, intelligence, communication, facility and so forth [16]. Although service design increases the service cost of service members, it has many advantages. For example, service design can ensure the timely maintenance of products, extend the use time of products and improve the use value of consumers [17]. Further, service design can facilitate interaction between enterprises and consumers [16]. High quality service can improve the social reputation of enterprises and increase the market demand for products. The abovementioned benefits further confirm the positive effect of service design on the sustainable development of enterprises [18]. Many enterprises recognise these benefits and actively implement service design. Taking electric vehicles as an example, BYD has designed an electric vehicle service management system to monitor the performance of electric vehicle batteries and engines and provide timely feedback to consumers to ensure in turn timely maintenance of electric vehicles. In addition to the service guarantee provided by manufacturers, retailers have successively launched similar services [19]. For example, the Great Wall Motors Hefei Automobile Sales Service Shop 4S installs vehicle monitoring systems for electric vehicles. It can monitor the health of electric vehicles and provide reasonable control and early warning services for engines and electric energy. According to the above existing practices, service design can be provided by both

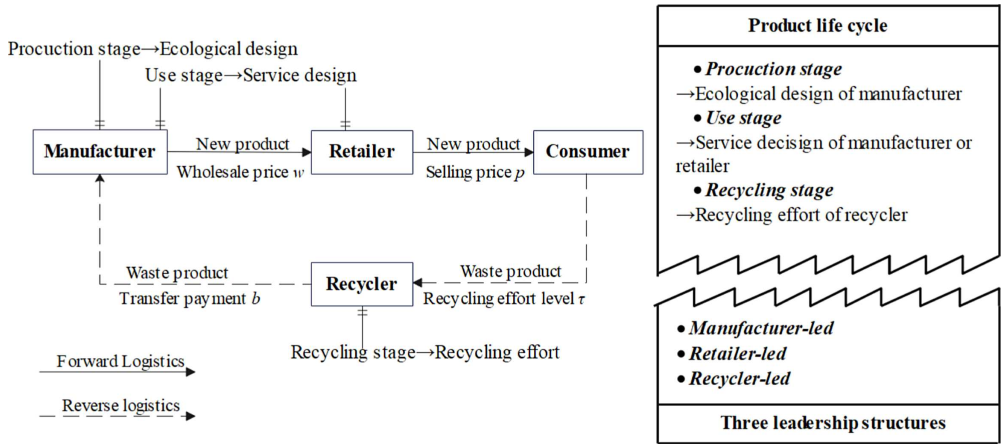

FIGURE 1. The research framework of this paper.

manufacturer and retailer. Previous studies have shown that the same investment behaviour of members at different levels has varying effects on the production, recycling and profit distribution of the CLSC [20]. Therefore, we can raise an important scientific question: Who provides service design that is more conducive to the operation of the system – the manufacturer or the retailer? Inspired by this question, the focus of this study is to provide guidance for the CLSC to select the optimal service design member.

The background and existing research described above show that from the perspective of life cycle management (*i.e.*, ecological design, service design and recycling), studying the CLSC operation problem can help improve the overall sustainable development of the CLSC system. Essentially, the CLSC system contains multi-level members, and there are differences in the behaviour and decision-making of members at different levels [21]. Previous studies have shown that the transfer of dominant power in the system is an important factor affecting the behaviour of members, market demand and profit distribution [2,22]. Many scholars, such as [23,24], believe that manufacturer leadership or retailer leadership in the CLSC are more conducive to the operation of the system and improves system recycling efficiency. However, these studies did not consider the scenario in which recyclers lead CLSCs. With the continuous deepening of green concepts among governments and consumers, recyclers have gradually become a crucial decision-making member in CLSCs [25]. For example, in terms of the recycling channel, Greenland has signed agreements with over 500 vehicle and battery manufacturers to establish a targeted recycling network for waste batteries. This further proves that recyclers have the ability to lead the CLSC system. Therefore, from the life cycle perspective, studying the CLSC operational decision and optimal channel leadership structure for the system provides theoretical reference and practical guidance for establishing a new sustainable CLSC management mode.

Based on the background explained above, for the sustainable development of the CLSC, from the product life cycle perspective – ecological design, service design and recycling effort – we study the CLSC operation decisions under different leadership structures (*i.e.*, manufacturer-led, retailer-led and recycler-led). The system operation decisions under different scenarios are given, and the optimal leadership structure and the selection strategy of service design members are clarified. Specifically, the research framework of this paper is shown in Figure 1.

Following are the problems to be addressed in this paper.

– How does the adoption of ecological design and service design in the CLSC affect the pricing decision, ecological design level, service design level, recycling effort level, and the profits of members and the system?

– When the manufacturer and the retailer act as service design providers, respectively, which is the optimal leadership structure from the perspective of the sustainable development of the CLSC? What are the main factors affecting the choice of an optimal leadership structure?
– When manufacturer, retailer and recycler are leaders, respectively, what is the selection strategy of the best service designer? What are the main factors that affect optimal service designer selection strategy?

In this paper, we design a game theory model to capture the interaction among manufacturer, retailer, recycler and consumer. According to different leadership structures and service design providers, six CLSC decision models are developed. By comparing the equilibrium results in different decision situations, we determine the profits of members and the whole CLSC, the selection conditions of the optimal leadership structure and the selection strategy of the optimal service design provider. The contributions of this paper are as follows. (1) This paper explores the CLSC operational decision from a new perspective, that is, the product life cycle (ecological design, service design, recycling). This perspective is meaningful because it can realise the sustainable development of CLSC from the process of production → use → recycling of the product, reduce the product carbon emission and improve the product service life. Moreover, this paper considers the recycler-led structure in the CLSC system; compares the CLSC operation problems under the manufacturer-led, retailer-led and recycler-led approaches; and explains the optimal leadership structure of the system. This has theoretical and practical significance for the establishment of a new sustainable CLSC system management mode. (2) In this study, the ecological design, service design and recycling effort behaviour are introduced into members' profit maximisation decision goals using game theory, and the CLSC decision model under different leadership structures is constructed. Through the logic of "model construction → model solution → decision analysis", the best operation decisions of the supply chain system under different decision scenarios are provided. This bridges the gap between interdisciplinary research ideas and research methodologies. (3) We present the optimal operational decisions for the system in different scenarios. First, the recycler-led channel structure is the best choice for the whole CLSC system. Second, from the perspective of the service design provider, when the manufacturer (retailer) acts as the leader, the best operation strategy is for the retailer (manufacturer) to provide the service design. However, when the recycler is the leader, either the manufacturer or the retailer providing the service design is the best operational strategy for the system. Our research conclusion provides decision-making support for CLSC members.

Our paper is structured as follows. The second section gives a literature review, while the third provides the problem description and assumptions. The fourth section details the model construction and solution, and the fifth gives a comparative analysis of the equilibrium results. The sixth section provides numerical examples and management recommendations, and finally, the last section suggests conclusions and future research interests.

2. Literature review

The literature related to this study can be categorized into four streams, that is, CLSC under different leadership structures, supply chain under ecological design, supply chain under service design and product life cycle management.

2.1. CLSC operation decisions under different leadership structures

This stream has achieved fruitful results. By classifying and collating the literature, it can be further divided into three types. The first is CLSC operation decision under a single leadership structure, such as manufacturer-led [26], retailer-led [24] and recycler-led [25]. The above studies all assumed that CLSCs have a single leadership structure and constructed system operation decision models in different scenarios. Finally, they found that regardless of the leadership structure, CLSCs can help achieve a green economy. The second type of research assumes that members at same layer in the CLSC system are in Nash non cooperative game. For example, considering the low-carbon preference of consumers, a CLSC network operation decision was discussed by Cheng *et al.* [27], who found that an increase in low-carbon preference is more conducive to improving the recycling rate of waste products. Taking an automobile CLSC as their research case, Fander and Yaghoubi [28] developed a

CLSC decision model considering the manufacturers' CO2e reduction. Finally, they found that manufacturers' CO2e reduction behaviour can effectively promote manufacturers' investment in energy-saving technologies. However, the CLSC operation problem from the perspective of supply chain network structure cannot describe the game relationship between upstream and downstream members. The third type is CLSC operation decision under different leadership structures. Regarding the latter type, Choi *et al.* [29] focused on single-channel CLSC system, and explored the recycling decision and supply chain coordination under different leadership structures. The authors found that the retailer-led mode is more favourable to system operation. From the perspective of fuzzy demand, Liu *et al.* [30] established a CLSC decision model under different leadership structures and proved that the waste product recycling rate was the largest under the manufacturer-led mode. From the perspective of manufacturer-led, retailer-led and no-led structures, Zheng *et al.* [22] studied a CLSC decision problem of the manufacturer encroaching on retail channels, finding that retailers gain most benefit under the manufacturer-led structure. Taking the electric vehicle as a case, Liu *et al.* [31] constructed CLSC decision models considering supplier/manufacturer-led. These scholars suggested the impact of parameter changes on the CLSC equilibrium results in different situations. However, the abovementioned studies only consider reverse recycling in CLSCs, while ecological design and service design, which are key indicators to measure the sustainable operation of CLSCs, are not considered.

In the abovementioned research on the operation decisions of CLSCs under different leadership structures, the research methods fall into two categories. The first research method assumes that a CLSC system has a single/different leadership structure and uses game theory and the backward induction method to construct CLSC decision models from different perspectives (uncertain residual capacity [31], fairness concerns [24] and fuzzy demand [30]). By solving these decision models, the system equilibrium decisions are obtained. The second category of research method takes network structure CLSC systems as the research object and assumes that the members of each layer of the CLSC network system have equal power. Studies taking this approach used Nash non-cooperative game theory and the variational inequality method to establish the CLSC network decision models in different scenarios (*e.g.*, CO2e reduction behaviour of members [28] and consumer low-carbon preference [27]). In addition, these studies mostly employed modified projection algorithms to solve network equilibrium models and obtain system equilibrium decisions. It is worth noting that Nash non-cooperative game theory cannot describe the decision order between upper and lower levels members of the CLSC system; however, Stackelberg game theory can effectively describe the leadership power among members at each level. Therefore, we use Stackelberg game theory to describe the leadership relationships of each member in the CLSC system.

2.2. Supply chain operation decision under product ecological design

The origin of the product ecological design concept developed from the sustainable development idea, which aims to realize environmental protection in the production process while considering maximum profit of the enterprise. Mohtashami *et al.* [32], Garg *et al.* [33] and Fathollahi-Fard and Hajiaghaei-Keshteli [34] studied the ecological/green design problem of CLSC from the perspectives of transportation, product flow and environmental uncertainty, and found that, the implementation of ecological design for CLSC can reduce the system's disutility to the environment. However, all the above scholars studied the design of supply chain from the centralization perspective. Another kind of scholars take the decentralized CLSC as the research object and use the game theory to study the operation of the CLSC based on ecological design. From the perspective of manufacturer's green design, Jian *et al.* [35] studied a CLSC pricing decisions with fairness concern, finding that manufacturer's fairness concern behaviour has a negative impact on the environmental performance of green products. Taking competitive supply chain as the research object, Zhang *et al.* [36] designed a supply chain game model under the condition that two manufacturers implement green technology simultaneously, and they analysed the impact of technology investment level and green cost on system operation decision. They concluded that green investment is always beneficial to retailer, and the manufacturer's green investment is conducive to alleviating competition. The aforementioned research only considered the manufacturer's ecological design; however, from the perspective of the green product production cost sharing of manufacturer and retailer, Hong and Guo [37] proved that while the cost-sharing contract is not conducive to retailer's profit, it is beneficial to maximize social welfare. Meanwhile, considering green production investment and green marketing, Shi *et al.* [20] compared the impact of green production investment and green marketing by manufacturer and retailer. They found that implementation of green production investment and green marketing by the manufacturer is more benefit to supply chain green operation. Regarding the CLSC system, Li *et al.* [38] regarded CO2e reduction investment as the manufacturer's ecological design behaviour and designed CLSC decision models under different game structures. They concluded that CO2e reduction cooperation between manufacturer and retailer is more conducive to the sustainable operation of the system. Additionally, other scholars studied the CLSC operation decision from the perspectives of green innovation [39], green product innovation [40] and product design [41]. They all introduced the level of green design or ecological design of products as parameters into the decision models of the decision-makers. These scholars found that, regardless of external environment, the higher the green or ecological design level of manufacturer, the more benefit to the green operation of supply chains. However, the abovementioned research considered members' behaviour only in the product production stage and did not explore members' behaviour in the product use stage.

From the perspective of the research methods described in the summary of the literature above, the methods can be divided into three categories. The first is based on queuing theory. In this type of research, ecological design of the CLSC is performed from the perspective of the transportation impact on the environment, and queuing theory is used to study the optimisation operation of the whole system, for example, in Mohtashami *et al.* [32]. The second category of research methods uses multi-objective nonlinear programming to build a CLSC network optimisation model and realise the Pareto optimisation of the system by solving the model. For example, Garg *et al.* [33] and Fathollahi-Fard and Hajiaghaei-Keshteli [34]. The third type of research method employs game theory to introduce ecological design into the supply chain member's objective function and/or market demand function to build a CLSC decision model. Through solving the model, the impact of ecological design level on the supply chain equilibrium decision is obtained. Examples of this latter method in the literature are Jian *et al.* [35] and Shi *et al.* [20]. To sum up, the three research methods study system operation from the perspective of environmentally sustainable development. However, owing to differences in the research methods and model construction, different conclusions are obtained. Regarding the operational decision of the CLSC system, the game model describes the interactive relations among members well and considers differences in the behaviours and decisions of each member. Therefore, this study uses the game theory method to construct the system decision model and obtain the impact of ecological design level on the production, recycling and profit distribution of the CLSC system.

2.3. Supply chain operation decision under product service design

This stream of the literature is the supply chain operation decision from the perspective of product service design. In earlier studies, Hwang [42] studied the supply chain logistics system design under service level. Based on the principal-agent model, the influence of after-sales service level on supply chain performance was studied by Kim *et al.* [43], who determined the best service contract design of the system. Later, scholars paid attention to supply chain decision and studied the impact of enterprise service investment on the supply chain operation decision. From the perspective of retailer service investment, Zhang *et al.* [19] constructed a retailer-led decision model and proved that retailer service investment can lead to Pareto improvement of members. Song *et al.* [16] expanded the study of Zhang *et al.* [19], under the assumption of manufacturer and retailer service investment, they designed a dual-channel supply chain game model, concluding that, no matter who makes service investment, the dual-channel service model is superior to the single-channel service model. The abovementioned research considered only the impact of service investment on system operation and performance and did not study the impact of service level on the environment from the CLSC perspective. Considering network platform services provided by manufacturer for consumers, Wang *et al.* [44] studied the CLSC operation mode and discovered that consumers' sensitivity to online services is conducive to reducing the service cost coefficient and increasing the recycling efficiency. From the perspective of consumer service level sensitivity, the operation and coordination problem of a CLSC was studied by Hosseini-Motlagh *et al.* [45], who found that the consumer service sensitivity level affects the CLSC operational efficiency, and the expense-sharing contract can achieve supply chain coordination. Considering that the retailer provides maintenance and recycling services for consumers, Kong *et al.* [46] constructed the dual channel CLSC decision models under the manufacturer-led structure. Through solving these CLSC decision models, they found that improving retailer's service level can increase product sales price. In addition, the CLSC pricing decisions under different remanufacturing modes were studied by Zhao *et al.* [47], who found that the service level of the system and the recycling rate of waste products are higher under retailer remanufacturing. In sum, in the research on CLSCs considering service level, most scholars considered the impact of service behaviour on the CLSC decisions. This can determine only the impact of service provision on system operation in the process of product use. However, research on the CLSC decision has not been conducted from the product life cycle perspective.

In the existing research based on the service design of the CLSC, scholars have introduced service level into the supply chain decision model to study the impact of service level on the system operation decision. The introduction of service level can be divided into two categories. The first introduces the service level into the consumer utility function and constructs a CLSC decision model using consumer utility choice theory, as shown by Zhang *et al.* [19]. The second category directly introduces the service level into the demand function and describes the positive promotion effect of service level and consumer preference on demand, for example, Zhou *et al.* [48] and Kong *et al.* [46]. Our study is similar to that of Zhou *et al.* [48], except that we additionally consider the impact of ecological design on the consumer demand function and study the CLSC operation decision problem considering both ecological design and service design.

2.4. Product life cycle management

The fourth stream identified in the literature is product life cycle management, which originates from the concept of product management [49]. Wang *et al.* [50] considered that product life cycle management involves various businesses and management of the full life cycle of products, including product design, manufacturing, service and recycling. An examination of the existing literature produced two categories in this stream. The first category is the benefit evaluation of product life cycle management. Studies in this category examined the influence of life cycle management on product CO2e, environment and organizational performance from the perspective of product life cycle. For example, for the estimation of CO2e, Qiao *et al.* [51] estimated the CO2e from manufacturing technology, drive cycle and the recycling process, and found that life cycle management can reduce CO2e by half. From the perspective of battery life cycle cost, Delucchi and Lipman [52] proved that when battery manufacturing cost is lower or service life is longer, electric vehicles are more competitive than fuel vehicles. Through actual cases, Pinna *et al.* [53] argued that the implementation of product life cycle management is benefit to improving enterprise performance-related. The second category of studies considered how to implement and extend the product life cycle. In these studies, scholars studied how to improve product life cycle management from the perspectives of big data development [54], blockchain technology [55] and product intelligent auxiliary systems [56]. In the context of a CLSC system, Patroklos *et al.* [57] studied the impact of life cycle on the capacity planning of the system. The coordination problem considering product life cycle was studied by Asl-Najafi and Yaghoubi [58], who found that a mixed contract can satisfy Pareto optimality in the product life cycle model.

The above paper employs three types of research method. The first type describes the game relationship between the supply chain members using game theory, constructs CLSC decision models considering life cycle management and uses the backward induction to calculate the CLSC equilibrium results, such as in Asl-Najafi and Yaghoubi [58]. The second type uses the system dynamics method to construct a CLSC comprehensive capability dynamic model of product life cycle and study the impact of life cycle management on the operation and strategy of CLSC, for example, Patroklos *et al.* [57]. The third method is the empirical research method, which examines the product life cycle management of CLSC through data collection and analysis, such as in studies by Pinna *et al.* [53] and Qiao *et al.* [51]. In this study, similarly to the assumption of Asl-Najafi and Yaghoubi [58], the game method is used to construct CLSC decision models under different scenarios. However, it is important to note that the studies in this literature stream did not explore the operation decision and leadership structure selection of the CLSC from the life cycle perspective.

Table 1. Comparison between this paper and the main related literature.

Literature	Leadership structure				PLC				Method	
	ML	SL	RL	Other	ED	SD	Re	Other	GT	Other
Genc and Giovanni [23], Xiao *et al.* [26], Huang and Wang [59]	✓						✓		✓	
Wang *et al.* [4], Yi *et al.* [24]		✓					✓		✓	
Cai *et al.* [25]			✓				✓		✓	✓
Cheng *et al.* [27], Fander and Yaghoubi [28]				✓			✓		✓	
Choi *et al.* [29], Liu *et al.* [30]	✓	✓	✓	✓			✓		✓	
Zheng *et al.* [22]	✓	✓		✓			✓		✓	
Liu *et al.* [31]	✓			✓			✓		✓	
Gouping and Sulin [60]				✓			✓		✓	
Mohtashami *et al.* [32], Garg *et al.* [33], Fathollahi-Fard and Hajiaghaei-Keshteli [34]					✓		✓			✓
Jian *et al.* [35]	✓			✓	✓		✓		✓	
Zhang *et al.* [36], Shi *et al.* [20]	✓				✓				✓	
Hong and Guo [37], Li *et al.* [38]	✓			✓	✓				✓	
Wong *et al.* [39]					✓					✓
Reimann *et al.* [40], Liu *et al.* [41]				✓	✓		✓		✓	
Hwang [42], Kim *et al.* [43]						✓				✓
Zhang *et al.* [19]		✓				✓			✓	
Song *et al.* [16]	✓					✓			✓	
Wang *et al.* [44]	✓					✓	✓		✓	
Hosseini-Motlagh *et al.* [45], Kong *et al.* [46]	✓			✓		✓	✓		✓	
Zhao *et al.* [47]	✓	✓				✓	✓		✓	
Wang *et al.* [50], Qiao *et al.* [51], Liu *et al.* [55], Zheng *et al.* [56]								✓		✓
Asl-Najafi and Yaghoubi [58]	✓			✓			✓	✓	✓	
This paper	✓	✓	✓		✓	✓	✓		✓	

Notes. ML: manufacturer-led. SL: retailer-led. RL: recycler-led. GT: game theory. PLC: product life cycle. ED: ecological design. SD: service design. Re: recycling.

2.5. Research gaps

In summary, our literature review reveals several gaps in the focus of studies, as follows:

(1) In the existing studies on the CLSC, scholars focused mainly on the product recycling and remanufacturing process. However, recycling and remanufacturing can only solve the problem of waste product reuse and not that of green economy in the production and use process of products. From the product life cycle perspective – green design, service design and recycling effort – studies studying the operation decision of a CLSC have been scarce. Meanwhile, under the assumption of product life cycle, introducing the recycler-led approach into the CLSC and studying the optimal leadership structure selection of the CLSC has not been explored.

(2) In the research into the CLSC operation decision under ecological design and service design, most scholars have assumed enterprise ecological design or service design. However, under the double assumptions of ecological design and service design, and considering different leadership structures (manufacturer-led, retailer-led and recycler-led), studies that explored the service design provider selection strategy and the CLSC operation decision have still been extremely scarce.

(3) In existing research on product life cycle management, scholars have assessed the product life cycle and how to improve the product life cycle management mode. However, for a CLSC system, the product life cycle needs to progress through the stages of production/remanufacturing, use and recycling, which are also various aspects of the CLSC system. In the current research, there is a lack of studies on product life cycle management from the perspective of the CLSC. Therefore, based on the above research gaps, this paper studies the CLSC operation decision and leadership structure selection problems from a product life cycle perspective, which supplements the literature on CLSC decision.

Specifically, a detailed comparison between this paper and the main related literature is shown in Table 1. Therefore, according to the research gaps, from the product life cycle perspective (*i.e.*, ecological design, service design and recycling effort), this paper studies the operation decisions problem of the CLSC under different leadership structures (*i.e.*, manufacturer-led, retailer-led and recycler-led), which supplements the literature on CLSC operation management.

3. Problem description and assumptions

3.1. Problem description

This study assumes that a CLSC system consists of a manufacturer, a retailer and a recycler. The manufacturer is responsible for the production of products, the remanufacturing of waste products and wholesale products to the retailer. The retailer sells products according to market demand. Referring to Liu *et al.* [61], assume that the recycler is responsible for the recycling of waste products. The reason for this assumption is that with continuous growth of the market scale of waste products, the recycling rate of waste products has lagged far behind the waste product production rate. Therefore, an important way to protect the environment is to train recyclers with professional qualifications to recycle waste products. According to Sahebi *et al.* [62], CLSC members are risk neutral and the information among members is completely symmetrical. Each member of the system aims to maximize their profits, and there is a Stackelberg game relationship between upper and lower members [3]. According to Choi *et al.* [29] and Cai *et al.* [25], assume that manufacturer, retailer and recycler have the ability to act as the leaders of the Stackelberg game; that is, manufacturer, retailer and recycler can be the leaders of the system, and non-leading members can make their own optimal decisions according to the decisions of the leading member.

To promote the CLSC sustainable development under the three leadership structures (*i.e.*, manufacturer-led, retailer-led and recycler-led), this paper introduces the concept of product life cycle management into the system. That is, in addition to recycling and remanufacturing, we also take ecological design and service design into account in the CLSC. In terms of ecological design, according to Li *et al.* [38], assume that the manufacturer implements ecological design, which aims to reduce CO2e in the production process of products and achieve a green economy. At the same time, in terms of service design, referring to the research of Song *et al.* [16], this study assumes that manufacturer and retailer can act as service design providers. Service design providers provide services during the use of products, including product performance monitoring, after-sales and maintenance. The CLSC decision models considering product life cycle management (*i.e.*, ecological design, service design and recycling effort) under three leadership structures are established. Analyse the system operation decisions under different scenarios, give the impact of ecological design, service design and recycling effort levels on the equilibrium decisions, and determine the optimal leadership structure and service design selection conditions of the system.

3.2. Model assumptions

The model assumptions underlying this study are as follows:

– Assume that the waste products recycled by the recycler have recycling value and can be used for remanufacturing [3]. The manufacturer remanufactures waste products. Remanufactured products are consistent with new products in performance and appearance. Consumers regard the two products as equal [29].

- According to Savaskan *et al.* [3], to avoid interference of initial and final period effects, assume that the behaviour sales and recycling of the CLSC system focuses only on the single cycle situation; that is, the forward sales and reverse recycling processes of products are completed in the same period. Many studies have made a similar assumption, such as Zhu *et al.* [1], Choi *et al.* [29] and Liu *et al.* [31].
- In terms of ecological design, assume that $c(g) = \frac{1}{2}\delta g^2$ is the total cost of the manufacturer for product ecological design, δ is the cost coefficient, and g is the manufacturer's ecological design level. In terms of service design, assume that $c(s_i) = \frac{1}{2}\eta s_i^2$, $i \in (m, r)$ are the service design cost of manufacturer and retailer respectively. Where s_i, $i \in (m, r)$ is the service design level of the manufacturer (retailer), η is the service design cost coefficient. In terms of waste product recycling, according to Savaskan *et al.* [3] and Kong *et al.* [46], assume that $c(\tau_t) = k\tau_t^2$ is the recycling effort cost of the recycler, where $0 \leq \tau_t \leq 1$ is the waste product recycling effort level, $k > 0$ is the scale parameter, and the scale parameter k indicates the difficulty of recycling.
- Referring to the study of Juhong *et al.* [63], the market demand is affected by product selling price, ecological design level and service design level. Assume that the demand function of the CLSC is $q = a - \beta p + \gamma g + \theta s_i$, $i \in (m, r)$. Where, a is the product market capacity, p is the product selling price, β indicates the sensitivity of consumers to product prices, $a > \beta p$, γ is the consumers' preference for the manufacturer's ecological design, and θ is the consumers' preference for the service design.

Finally, other symbols involved in the model and their descriptions are provided next: w is the wholesale price set by the manufacturer, c_m represents the manufacturer's unit fixed cost of using raw materials to produce new products, c_r is the manufacturer's unit fixed cost of remanufacturing using waste products. We set $\Delta = c_m - c_r$ represents the unit cost saved by the manufacturer through remanufacturing, and b is the unit transfer payment paid by the manufacturer to the recycler. To ensure that recycling and remanufacturing have certain economic significance to the manufacturer, $c_m - c_r - b > 0$ is required. π_X^{ij} refers to the profit of member X when member j is the service design provider under the leadership structure i, where $i = (M, R, T)$ represents the manufacturer-led, retailer-led and recycler-led structures, respectively, $j = (M, R)$ indicates that the manufacturer or retailer is the service design provider, respectively, and $X = (m, r, t, s)$ represents the manufacturer, retailer, recycler and the whole CLSC system.

4. Game analysis with different service design providers

In order to comprehensively discuss the impact of different leadership structures and different service design providers on the equilibrium and profit of CLSC members, Sections 4.1 and 4.2 successively provide three game equilibria when the manufacturer and retailer respectively act as service design providers.

4.1. Game analysis of manufacturer as the service design provider

This part first analyses the equilibrium under three leadership structures when the manufacturer acts as the service design provider. At this time, the consumer demand is $q = a - \beta p + \gamma g + \theta s_m$. This section will be analyses in the following order: Sections 4.1.1–4.1.3 describe the equilibrium wholesale price, selling price, ecological design level, service design level and recycling effort level in the game of manufacturer-led Stackelberg, retailer-led Stackelberg and recycler-led Stackelberg. The profit decision model of CLSC members as follows:

$$\pi_m(w, g, s_m) = (w - c_m)q - \frac{1}{2}\delta g^2 - \frac{1}{2}\eta s_m^2 + (\Delta - b)\tau_t q \tag{4.1}$$

$$\pi_r(p) = (p - w)q \tag{4.2}$$

$$\pi_t(\tau_t) = b\tau_t q - k\tau_t^2. \tag{4.3}$$

4.1.1. Manufacturer-led Stackelberg (MM)

In the case of manufacturer-led and acts as the service design provider, the manufacturer first announces the wholesale price w^{MM}, the ecological design g^{MM} and the service design level s_m^{MM}; the retailer and recycler then determine the selling price p^{MM} and the recycling effort level τ_t^{MM}. According to the above game sequence, the backward induction method is adopted to solve, and Proposition 4.1 is obtained.

Proposition 4.1. *In the case of manufacturer-led and acts as the service design provider, the equilibrium strategy of each member as follows.*

The equilibrium strategies of manufacturer are

$$w^{\mathrm{MM}^*}=\frac{a\eta\delta(2k-\beta b(\Delta-b))+kc_m\left(2\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)}{k(2\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b))},$$
$$g^{\mathrm{MM}^*}=\frac{k\eta\gamma(a-\beta c_m)}{k(2\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b))},$$
$$s_m^{\mathrm{MM}^*}=\frac{k\delta\theta(a-\beta c_m)}{k(2\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b))}.$$

The equilibrium strategy of retailer is $p^{\mathrm{MM}^*}=\frac{a\eta\delta(3k-\beta b(\Delta-b))+kc_m\left(\eta\delta\beta-\eta\theta^2-\delta\gamma^2\right)}{k(2\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b))}$.

The equilibrium strategy of recycler is $\tau_t^{\mathrm{MM}^*}=\frac{b\eta\delta\beta(a-\beta c_m)}{2(k(2\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))}$.

The consumer demand is $q^{\mathrm{MM}^*}=\frac{k\eta\delta\beta(a-\beta c_m)}{k(2\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b))}$.

The profit of each CLSC member is $\pi_m^{\mathrm{MM}^*}=\frac{k\eta\delta(a-\beta c_m)^2}{2(k(2\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))}$, $\pi_r^{\mathrm{MM}^*}=\frac{k^2\eta^2\delta^2\beta(a-\beta c_m)^2}{(k(2\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))^2}$, $\pi_t^{\mathrm{MM}^*}=\frac{kb^2\eta^2\delta^2\beta^2(a-\beta c_m)^2}{4(k(2\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))^2}$, *the profit of the whole CLSC is* $\pi_s^{\mathrm{MM}^*}=\pi_m^{\mathrm{MM}^*}+\pi_r^{\mathrm{MM}^*}+\pi_t^{\mathrm{MM}^*}$.

Lemma 4.1. *To ensure that the model MM has a unique equilibrium result and each expression has economic significance, the parameters must be satisfied:* $\eta>\frac{\theta(\theta+\gamma+2\beta(\Delta-b)+a-\beta c_m)}{4\beta}$, $\delta>\frac{\gamma(\theta+\gamma+2\beta(\Delta-b)+a-\beta c_m)}{4\beta}$, $k>\frac{b(\theta+\gamma+2\beta(\Delta-b)+a-\beta c_m)}{8}$, $a>\beta c_m$ *and* $\beta>\frac{\gamma^2}{\delta}+\frac{\theta^2}{\eta}$.

The conditions given by Lemma 4.1 firstly ensure that the objective function of CLSC members is concave, that is, there is a unique equilibrium strategy. At the same time, it also satisfies the economic feasibility of the theoretical model. This reveals that the investment cost coefficients for supply chain members to adopt ecological design, provide service design and recycle waste products are very high, so it is not economically feasible for members to spare no effort to invest (see similar assumption of Savaskan *et al.* [3]). In addition, β indicates that consumers' sensitivity to price should be higher than a certain threshold, and this threshold is related to the value-cost coefficient ratio brought by ecological design and service design adopted by CLSC members. What needs to be explained is that Lemmas 4.2 and 4.3 illustrate the same problem, and will not be repeated.

4.1.2. Retailer-led Stackelberg (RM)

In the case of retailer-led and manufacturer acts as the service design provider, the retailer first announces the selling price p^{RM}; the manufacturer and the recycler then determine the wholesale price w^{RM}, the ecological design level g^{RM}, the service design level s_m^{RM} and the recycling effort level τ_t^{RM}. According to the above game sequence, the backward induction method is adopted to solve, and Proposition 4.2 can be obtained.

Proposition 4.2. *In the case of retailer-led and manufacturer acts as the service design provider, the equilibrium strategy of each member as follows.*

The equilibrium strategies of manufacturer are

$$w^{\mathrm{RM}^*}=\frac{4kc_m\left(\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)+\eta\delta(2k-\beta b(\Delta-b))(a+\beta c_m)}{2(2k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))},$$

$$g^{\mathrm{RM}^*} = \frac{k\eta\gamma(a-\beta c_m)}{2k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b))},$$
$$s_m^{\mathrm{RM}^*} = \frac{k\delta\theta(a-\beta c_m)}{2k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b))}.$$

The equilibrium strategy of retailer is $p^{\mathrm{RM}^*} = \frac{a\eta\delta b(2k-\beta b(\Delta-b))+k\left(\eta\delta\beta-\eta\theta^2-\delta\gamma^2\right)(a+\beta c_m)}{\beta(2k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))}$.

The equilibrium strategy of recycler is $\tau_t^{\mathrm{RM}^*} = \frac{b\eta\delta\beta(a-\beta c_m)}{2(2k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))}$.

The consumer demand is $q^{\mathrm{RM}^*} = \frac{k\eta\delta\beta(a-\beta c_m)}{2k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b))}$.

The profit of each CLSC member is $\pi_m^{\mathrm{RM}^*} = \frac{k^2\eta\delta(a-\beta c_m)^2}{2(2k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))^2}$, $\pi_r^{\mathrm{RM}^*} = \frac{k\eta\delta(a-\beta c_m)^2}{2(2k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))}$, $\pi_t^{\mathrm{RM}^*} = \frac{kb^2\eta^2\delta^2\beta^2(a-\beta c_m)^2}{4(2k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))^2}$, *the profit of the whole CLSC is* $\pi_s^{\mathrm{RM}^*} = \pi_m^{\mathrm{RM}^*} + \pi_r^{\mathrm{RM}^*} + \pi_t^{\mathrm{RM}^*}$.

Lemma 4.2. *To ensure that the model RM has a unique equilibrium result and each expression has economic significance, the parameters must be satisfied:* $\eta > \frac{\theta(2(\theta+\gamma+\beta(\Delta-b))+a-\beta c_m)}{4\beta}$, $\delta > \frac{\gamma(2(\theta+\gamma+\beta(\Delta-b))+a-\beta c_m)}{4\beta}$, $k > \frac{b(2(\theta+\gamma+\beta(\Delta-b))+a-\beta c_m)}{8}$, $a > \beta c_m$ *and* $\beta > \frac{\gamma^2}{\delta} + \frac{\theta^2}{\eta}$.

4.1.3. Recycler-led Stackelberg (TM)

In the case of recycler-led and manufacturer acts as the service design provider, the recycler first announces the recycling effort level τ_t^{TM}; the manufacturer and the retailer then determine the wholesale price w^{TM}, the ecological design level g^{TM}, the service design level s_m^{TM} and the selling price p^{TM}. According to the above game sequence, the backward induction method is adopted to solve, and Proposition 4.3 can be obtained.

Proposition 4.3. *In the case of recycler-led and manufacturer acts as the service design provider, the equilibrium strategy of each member as follows.*

The equilibrium strategies of manufacturer are

$$\begin{aligned}
w^{\mathrm{TM}^*} &= \frac{a\eta\delta\left(2k\left(3\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)-\beta b(\Delta-b)\left(4\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)\right)}{2(3\eta\delta\beta-\delta\theta^2-\eta\gamma^2)(k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))} \\
&\quad + \frac{c_m\left(2\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)\left(2k\left(\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)+\eta\delta\beta(4k-\beta b(\Delta-b))\right)}{2(3\eta\delta\beta-\delta\theta^2-\eta\gamma^2)(k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))}, \\
g^{\mathrm{TM}^*} &= \frac{\eta\gamma\left(2k\left(\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)+\eta\delta\beta(2k-\beta b(\Delta-b))\right)(a-\beta c_m)}{2(3\eta\delta\beta-\delta\theta^2-\eta\gamma^2)(k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))}, \\
s_m^{\mathrm{TM}^*} &= \frac{\delta\theta\left(2k\left(\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)+\eta\delta\beta(2k-\beta b(\Delta-b))\right)(a-\beta c_m)}{2(3\eta\delta\beta-\delta\theta^2-\eta\gamma^2)(k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))}.
\end{aligned}$$

The equilibrium strategy of retailer is

$$\begin{aligned}
p^{\mathrm{TM}^*} &= \frac{a\eta\delta\left(4k\left(3\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)-\beta b(\Delta-b)\left(5\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)\right)}{2(3\eta\delta\beta-\delta\theta^2-\eta\gamma^2)(k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))} \\
&\quad + \frac{c_m\left(\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)\left(2k\left(\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)+\eta\delta\beta(4k-\beta b(\Delta-b))\right)}{2(3\eta\delta\beta-\delta\theta^2-\eta\gamma^2)(k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))}.
\end{aligned}$$

The equilibrium strategy of recycler is $\tau_t^{\mathrm{TM}^*} = \frac{b\eta\delta\beta(a-\beta c_m)}{2(k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))}$.

The consumer demand is $q^{\mathrm{TM}^*} = \frac{\beta\eta\delta\left(2k\left(\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)+\eta\delta\beta(2k-\beta b(\Delta-b))\right)(a-\beta c_m)}{2(3\eta\delta\beta-\delta\theta^2-\eta\gamma^2)(k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))}$.

The profit of each CLSC member is

$$\pi_m^{\mathrm{TM}^*} = \frac{\eta\delta\left(2\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)\left(2k\left(\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)+\eta\delta\beta(2k-\beta b(\Delta-b))\right)^2(a-\beta c_m)^2}{8(3\eta\delta\beta-\delta\theta^2-\eta\gamma^2)^2\left(k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b))\right)^2},$$

$$\pi_r^{\mathrm{TM}^*} = \frac{\eta^2\delta^2\beta\left(2k\left(\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)+\eta\delta\beta(2k-\beta b(\Delta-b))\right)^2(a-\beta c_m)^2}{4(3\eta\delta\beta-\delta\theta^2-\eta\gamma^2)^2\left(k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b))\right)^2},$$

$$\pi_t^{\mathrm{TM}^*} = \frac{\eta^2\delta^2 b^2\beta^2(a-\beta c_m)^2}{4(3\eta\delta\beta-\delta\theta^2-\eta\gamma^2)(k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))},$$

and the profit of the whole CLSC is $\pi_s^{\mathrm{TM}^*} = \pi_m^{\mathrm{TM}^*} + \pi_r^{\mathrm{TM}^*} + \pi_t^{\mathrm{TM}^*}$.

Lemma 4.3. *To ensure that the model TM has a unique equilibrium result and each expression has economic significance, the parameters must be satisfied:* $\eta > \frac{\theta(\theta+\gamma+\beta(\Delta-b)+a-\beta c_m)}{3\beta}$, $\delta > \frac{\gamma(\theta+\gamma+\beta(\Delta-b)+a-\beta c_m)}{3\beta}$, $k > \frac{b(2\beta(\Delta-b)+a-\beta c_m)(\theta+\gamma+\beta(\Delta-b)+a-\beta c_m)}{8}$, $a > \beta c_m$ *and* $\beta > \frac{\gamma^2}{\delta} + \frac{\theta^2}{\eta}$.

4.2. Game analysis of retailer as the service design provider

We will discuss the equilibrium of three leadership structures when the retailer acts as the service design provider in this section. At this time, the consumer demand is $q = a - \beta p + \gamma g + \theta s_r$. Similar to the structure of Sections 4.1, 4.2.1–4.2.3 describe the equilibrium strategies of the CLSC members in the game of manufacturer-led Stackelberg, retailer-led Stackelberg and recycler-led Stackelberg. The profit decision model of CLSC members as follows:

$$\pi_m(w,g) = (w-c_m)q + (\Delta-b)\tau_t q - \frac{1}{2}\delta g^2 \tag{4.4}$$

$$\pi_r(p,s_r) = (p-w)q - \frac{1}{2}\eta s_r^2 \tag{4.5}$$

$$\pi_t(\tau_t) = b\tau_t q - k\tau_t^2. \tag{4.6}$$

4.2.1. Manufacturer-led Stackelberg (MR)

In the case of manufacturer-led and retailer acts as the service design provider, the manufacturer first announces the wholesale price w^{MR} and the ecological level g^{MR}; the retailer and recycler then determine the selling price p^{MR}, the service design level s_r^{MR} and the recycling effort level τ_t^{MR}. According to the above game sequence, the backward induction method is adopted to solve, and Proposition 4.4 is obtained.

Proposition 4.4. *In the case of manufacturer-led and retailer acts as the service design provider, the equilibrium strategy of each member as follows.*

The equilibrium strategies of manufacturer are

$$w^{\mathrm{MR}^*} = \frac{ak\delta\left(\eta\beta-\theta^2\right)+a\eta\delta\beta(k-\beta b(\Delta-b))+kc_m\beta\left(3\eta\delta\beta-2\delta\theta^2-\eta\gamma^2\right)}{k(3\eta\delta\beta-2\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(k-\beta b(\Delta-b))},$$

$$g^{\mathrm{RM}^*} = \frac{k\eta\gamma(a-\beta c_m)}{k(3\eta\delta\beta-2\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(k-\beta b(\Delta-b))}.$$

The equilibrium strategies of retailer are

$$p^{\mathrm{MR}^*} = \frac{ak\delta\left(\eta\beta-\theta^2\right)+a\eta\delta\beta(2k-\beta b(\Delta-b))+kc_m\beta\left(\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)}{\beta(k(3\eta\delta\beta-2\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(k-\beta b(\Delta-b)))},$$

$$s_r^{\mathrm{MR}^*} = \frac{k\delta\theta(a-\beta c_m)}{k(3\eta\delta\beta-2\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(k-\beta b(\Delta-b))}.$$

The equilibrium strategy of recycler is $\tau_t^{\mathrm{MR}^*} = \frac{b\eta\delta\beta(a-\beta c_m)}{2(k(3\eta\delta\beta-2\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(k-\beta b(\Delta-b)))}$.

The consumer demand is $q^{\mathrm{MR}^*} = \frac{k\eta\delta\beta(a-\beta c_m)}{k(3\eta\delta\beta-2\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(k-\beta b(\Delta-b))}$.

The profit of each CLSC member is $\pi_m^{\mathrm{MR}^*} = \frac{k\eta\delta(a-\beta c_m)^2}{2(k(3\eta\delta\beta-2\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(k-\beta b(\Delta-b)))}$, $\pi_r^{\mathrm{MR}^*} = \frac{k^2\delta^2\eta(2\eta\beta-\theta^2)(a-\beta c_m)^2}{2(k(3\eta\delta\beta-2\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(k-\beta b(\Delta-b)))^2}$, $\pi_t^{\mathrm{MR}^*} = \frac{kb^2\eta^2\delta^2\beta^2(a-\beta c_m)^2}{4(k(3\eta\delta\beta-2\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(k-\beta b(\Delta-b)))^2}$, *the profit of the whole CLSC is* $\pi_s^{\mathrm{MR}^*} = \pi_m^{\mathrm{MR}^*} + \pi_r^{\mathrm{MR}^*} + \pi_t^{\mathrm{MR}^*}$.

Lemma 4.4. *To ensure that the model MR has a unique equilibrium result and each expression has economic significance, the parameters must be satisfied:* $\eta > \frac{\theta(2\theta+\gamma+2\beta(\Delta-b)+a-\beta c_m)}{4\beta}$, $\delta > \frac{\gamma(2\theta+\gamma+2\beta(\Delta-b)+a-\beta c_m)}{4\beta}$, $k > \frac{b(2\theta+\gamma+2\beta(\Delta-b)+a-\beta c_m)}{8}$, $a > \beta c_m$ *and* $\beta > \frac{\gamma^2}{\delta} + \frac{\theta^2}{\eta}$.

4.2.2. Retailer-led Stackelberg (RR)

In the case of retailer-led and acts as the service design provider, the retailer first announces the selling price p^{RR} and service design level s_r^{RR}; the manufacturer and the recycler then determine the wholesale price w^{RR}, the ecological design level g^{RR} and the recycling effort level τ_t^{RR}. According to the above game sequence, the backward induction method is adopted to solve, and Proposition 4.5 can be obtained.

Proposition 4.5. *In the case of retailer-led and acts as the service design provider, the equilibrium strategy of each member as follows.*

The equilibrium strategies of manufacturer are

$$w^{\mathrm{RR}^*} = \frac{2kc_m\left(2\eta\delta\beta-\delta\theta^2-2\eta\gamma^2\right)+\eta\delta(2k-\beta b(\Delta-b))(a+\beta c_m)}{2(k(3\eta\delta\beta-\delta\theta^2-2\eta\gamma^2)+\eta\delta\beta(k-\beta b(\Delta-b)))},$$
$$g^{\mathrm{RR}^*} = \frac{k\eta\gamma(a-\beta c_m)}{k(3\eta\delta\beta-\delta\theta^2-2\eta\gamma^2)+\eta\delta\beta(k-\beta b(\Delta-b))}.$$

The equilibrium strategies of retailer are

$$p^{\mathrm{RR}^*} = \frac{ak\delta\left(\delta\beta-\gamma^2\right)+a\eta\delta\beta(2k-\beta b(\Delta-b))+kc_m\beta\left(\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)}{\beta(k(3\eta\delta\beta-\delta\theta^2-2\eta\gamma^2)+\eta\delta\beta(k-\beta b(\Delta-b)))},$$
$$s_r^{\mathrm{RR}^*} = \frac{k\delta\theta(a-\beta c_m)}{k(3\eta\delta\beta-\delta\theta^2-2\eta\gamma^2)+\eta\delta\beta(k-\beta b(\Delta-b))}.$$

The equilibrium strategy of recycler is $\tau_t^{\mathrm{RR}^*} = \frac{b\eta\delta\beta(a-\beta c_m)}{2(k(3\eta\delta\beta-\delta\theta^2-2\eta\gamma^2)+\eta\delta\beta(k-\beta b(\Delta-b)))}$.

The consumer demand is $q^{\mathrm{RR}^*} = \frac{k\eta\delta\beta(a-\beta c_m)}{k(3\eta\delta\beta-\delta\theta^2-2\eta\gamma^2)+\eta\delta\beta(k-\beta b(\Delta-b))}$.

The profit of each CLSC member is $\pi_m^{\mathrm{RR}^*} = \frac{k^2\eta^2\delta(2\delta\beta-\gamma^2)(a-\beta c_m)^2}{2(k(3\eta\delta\beta-\delta\theta^2-2\eta\gamma^2)+\eta\delta\beta(k-\beta b(\Delta-b)))^2}$, $\pi_r^{\mathrm{RR}^*} = \frac{k\eta\delta(a-\beta c_m)^2}{2(k(3\eta\delta\beta-\delta\theta^2-2\eta\gamma^2)+\eta\delta\beta(k-\beta b(\Delta-b)))}$, $\pi_t^{\mathrm{RR}^*} = \frac{kb^2\eta^2\delta^2\beta^2(a-\beta c_m)^2}{4(k(3\eta\delta\beta-\delta\theta^2-2\eta\gamma^2)+\eta\delta\beta(k-\beta b(\Delta-b)))^2}$, *and the profit of the whole CLSC is* $\pi_s^{\mathrm{RR}^*} = \pi_m^{\mathrm{RR}^*} + \pi_r^{\mathrm{RR}^*} + \pi_t^{\mathrm{RR}^*}$.

Lemma 4.5. *To ensure that the model RR has a unique equilibrium result and each expression has economic significance, the parameters must be satisfied:* $\eta > \frac{\theta(\theta+2\gamma+2\beta(\Delta-b)+a-\beta c_m)}{4\beta}$, $\delta > \frac{\gamma(\theta+2\gamma+2\beta(\Delta-b)+a-\beta c_m)}{4\beta}$, $k > \frac{b(\theta+2\gamma+2\beta(\Delta-b)+a-\beta c_m)}{8}$, $a > \beta c_m$ *and* $\beta > \frac{\gamma^2}{\delta} + \frac{\theta^2}{\eta}$.

4.2.3. Recycler-led Stackelberg (TR)

In the case of recycler-led and retailer acts as the service design provider, the recycler first announces the recycling effort level τ_t^{TR}, the manufacturer and the retailer then determine the wholesale price w^{TR}, the ecological design level g^{TR}, the selling price p^{TR} and the service design level s_r^{TR}. According to the above game sequence, the backward induction method is adopted to solve, and Proposition 4.6 can be obtained.

Proposition 4.6. *In the case of recycler-led and retailer acts as the service design provider, the equilibrium strategy of each member and consumer demand are consistent with the model TM, which will not be listed again here. Only give the profit of each member and the whole CLSC, with specific results as follows.*

$$\pi_m^{\mathrm{TR}^*} = \frac{\eta^2\delta\left(2\delta\beta-\gamma^2\right)\left(2k\left(\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)+\eta\delta\beta(2k-\beta b(\Delta-b))\right)^2(a-\beta c_m)^2}{8(3\eta\delta\beta-\delta\theta^2-\eta\gamma^2)^2(k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))^2},$$

$$\pi_r^{\mathrm{TR}^*} = \frac{\eta\delta^2\left(2\eta\beta-\theta^2\right)\left(2k\left(\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)+\eta\delta\beta(2k-\beta b(\Delta-b))\right)^2(a-\beta c_m)^2}{8(3\eta\delta\beta-\delta\theta^2-\eta\gamma^2)^2(k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))^2},$$

$$\pi_t^{\mathrm{TR}^*} = \frac{\eta^2\delta^2 b^2\beta^2(a-\beta c_m)^2}{4(3\eta\delta\beta-\delta\theta^2-\eta\gamma^2)(k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))},$$

and the profit of the whole CLSC is $\pi_s^{\mathrm{TR}^*} = \pi_m^{\mathrm{TR}^*} + \pi_r^{\mathrm{TR}^*} + \pi_t^{\mathrm{TR}^*}$.

Lemma 4.6. *To ensure the model TR has a unique equilibrium result and each expression has economic significance, the parameters must be satisfied:* $\eta > \frac{\theta(\theta+\gamma+\beta(\Delta-b)+a-\beta c_m)}{3\beta}$, $\delta > \frac{\gamma(\theta+\gamma+\beta(\Delta-b)+a-\beta c_m)}{3\beta}$, $k > \frac{b(2\beta(\Delta-b)+a-\beta c_m)(\theta+\gamma+\beta(\Delta-b)+a-\beta c_m)}{8}$, $a > \beta c_m$ *and* $\beta > \frac{\gamma^2}{\delta} + \frac{\theta^2}{\eta}$.

5. Comparative analysis of equilibrium results

Some interesting results were obtained by comparing the equilibrium results of the CLSC in different decision models presented in Section 4. This section will be analyses in the following order: In this part, we focus on analysing and comparing the impact of differences in leadership structure and the service design provider on the equilibrium strategies and profit of CLSC members in Sections 5.1 and 5.2 respectively.

5.1. Comparative analysis of leadership channel structure

Conclusion 5.1. By comparing the equilibrium results in model MM, RM and TM when the manufacturer as the service design provider, we can get: $w^{\mathrm{RM}^*} < w^{\mathrm{TM}^*} < w^{\mathrm{MM}^*}$, $p^{\mathrm{TM}^*} < p^{\mathrm{RM}^*} < p^{\mathrm{MM}^*}$, $g^{\mathrm{TM}^*} > g^{\mathrm{RM}^*} > g^{\mathrm{MM}^*}$, $s_m^{\mathrm{TM}^*} > s_m^{\mathrm{RM}^*} > s_m^{\mathrm{MM}^*}$, $q^{\mathrm{TM}^*} > q^{\mathrm{RM}^*} > q^{\mathrm{MM}^*}$, $\tau_t^{\mathrm{TM}^*} > \tau_t^{\mathrm{RM}^*} > \tau_t^{\mathrm{MM}^*}$.

The analysis result of Conclusion 5.1 implies that the wholesale price is the highest under the manufacturer-led CLSC and the lowest under the retailer-led CLSC. Counterintuitively, the selling price is the lowest under the recycler-led CLSC, which is different from the research conclusion of Choi *et al.* [29]. This implies that in the case of the recycler-led channel structure, it forces the retailer to lower the selling price in order to obtain greater consumer demand, thus improving the recycler's recycling efforts level. At the same time, we also find that under the recycler-led channel structure, the ecological design level and service design level of manufacturer are also the highest. Therefore, through the above conclusions, in the context of manufacturer as the service provider, manufacturer-led CLSC is the most unfavorable for the sustainable operation of the system, while recycler-led CLSC is more conducive to the sustainable operation of the system, followed by the retailer-led CLSC.

Conclusion 5.2. By comparing the profit of each member and the whole system in model MM, RM and TM when the manufacturer as the service design provider, we can get:

(a) $\pi_m^{\mathrm{MM}^*} > \pi_m^{\mathrm{TM}^*} > \pi_m^{\mathrm{RM}^*}$, $\pi_t^{\mathrm{TM}^*} > \pi_t^{\mathrm{RM}^*} > \pi_t^{\mathrm{MM}^*}$, $\pi_s^{\mathrm{TM}^*} > \pi_s^{\mathrm{RM}^*} > \pi_s^{\mathrm{MM}^*}$;
(b) If $f_1(\gamma,\theta) \geq 0$, $\pi_r^{\mathrm{RM}^*} \geq \pi_r^{\mathrm{TM}^*} > \pi_r^{\mathrm{MM}^*}$; if $f_1(\gamma,\theta) < 0$, then, $\pi_r^{\mathrm{TM}^*} > \pi_r^{\mathrm{RM}^*} > \pi_r^{\mathrm{MM}^*}$. Where, $f_1(\gamma,\theta)$ is a binary function related to γ and θ and makes $\pi_r^{\mathrm{RM}^*} = \pi_r^{\mathrm{TM}^*}$.

The research results of (a) in Conclusion 5.2 first show that, for the manufacturer, the channel structure led by itself is always the most profitable, and the least under the case of retailer-led. However, the recycler and the whole system always get the largest profit under the recycler-led channel structure, and the least profit under the case of manufacturer-led. (b) Further indicates that, for the retailer, the channel structure led by itself is not always more profitable, and sometimes the case of recycler-led is more favorable to the retailer, which is mainly depending on the degree of consumer preference for the manufacturer's ecological design and service design level. Combined with Conclusion 5.1, the recycler-led CLSC is always superior to the case of the manufacturer-led or retailer-led. Specifically, the recycler-led channel structure is more conducive to promoting product selling and recycling, improving the ecological design and service design level of the CLSC, which is conducive to the sustainable operation of the whole system.

Conclusion 5.3. By comparing the equilibrium results in model MR, RR and TR when the retailer as the service design provider, we can get:

(a) $w^{\mathrm{RM}^*} < w^{\mathrm{TM}^*} < w^{\mathrm{MM}^*}$;
(b) if $\frac{\gamma^2}{\delta} \leq \frac{\theta^2}{\eta}$, $p^{\mathrm{TR}^*} < p^{\mathrm{MR}^*} \leq p^{\mathrm{RR}^*}$, $g^{\mathrm{TR}^*} > g^{\mathrm{MR}^*} \geq g^{\mathrm{RR}^*}$, $s_r^{\mathrm{TR}^*} > s_r^{\mathrm{MR}^*} \geq s_r^{\mathrm{RR}^*}$, $q^{\mathrm{TR}^*} > q^{\mathrm{MR}^*} \geq q^{\mathrm{RR}^*}$, $\tau_t^{\mathrm{TR}^*} > \tau_t^{\mathrm{MR}^*} \geq \tau_t^{\mathrm{RR}^*}$; if $\frac{\gamma^2}{\delta} > \frac{\theta^2}{\eta}$, then, $p^{\mathrm{TR}^*} < p^{\mathrm{RR}^*} < p^{\mathrm{MR}^*}$, $g^{\mathrm{TR}^*} > g^{\mathrm{RR}^*} > g^{\mathrm{MR}^*}$, $s_r^{\mathrm{TR}^*} > s_r^{\mathrm{RR}^*} > s_r^{\mathrm{MR}^*}$, $q^{\mathrm{TR}^*} > q^{\mathrm{RR}^*} > q^{\mathrm{MR}^*}$, $\tau_t^{\mathrm{TR}^*} > \tau_t^{\mathrm{MR}^*} > \tau_t^{\mathrm{RR}^*}$.

The analysis result of Conclusion 5.3 implies that the recycler-led channel structure is most efficient when the retailer acts as the service provider, this is consistent with Conclusion 5.1. By further comparison, we find that unlike the results when the manufacturer as the service design provider, the retailer-led channel structure is not always superior to the manufacturer-led situation. To be specific, when the value-cost ratio (*i.e.*, $\frac{\gamma^2}{\delta}$) generated by the manufacturer through ecological design is lower than that generated by the retailer through service design (*i.e.*, $\frac{\theta^2}{\eta}$), under the manufacturer-led channel structure, the whole CLSC has a lower selling price, a higher ecological design level and service design level, which also promotes consumer demand and the improvement of recycling efficiency. Otherwise, the retailer-led channel structure will be superior to the manufacturer-led situation.

Conclusion 5.4. By comparing the profit of each member and the whole system in model MR, RR and TR when the retailer as the service design provider, we can get:

(a) If $f_2(\gamma,\theta) \geq 0$, $\pi_m^{\mathrm{MR}^*} \geq \pi_m^{\mathrm{TR}^*} > \pi_m^{\mathrm{RR}^*}$; if $f_2(\gamma,\theta) < 0$, then, $\pi_m^{\mathrm{TR}^*} > \pi_m^{\mathrm{MR}^*} > \pi_m^{\mathrm{RR}^*}$;
(b) If $f_3(\gamma,\theta) \geq 0$, $\pi_r^{\mathrm{RR}^*} \geq \pi_r^{\mathrm{TR}^*} > \pi_r^{\mathrm{MR}^*}$; if $f_3(\gamma,\theta) < 0$, then, $\pi_r^{\mathrm{TR}^*} > \pi_r^{\mathrm{RR}^*} > \pi_r^{\mathrm{MR}^*}$;
(c) If $\frac{\gamma^2}{\delta} \leq \frac{\theta^2}{\eta}$, $\pi_t^{\mathrm{TR}^*} > \pi_t^{\mathrm{MR}^*} \geq \pi_t^{\mathrm{RR}^*}$, $\pi_s^{\mathrm{TR}^*} > \pi_s^{\mathrm{MR}^*} \geq \pi_s^{\mathrm{RR}^*}$; if $\frac{\gamma^2}{\delta} > \frac{\theta^2}{\eta}$, then, $\pi_t^{\mathrm{TR}^*} > \pi_t^{\mathrm{RR}^*} > \pi_t^{\mathrm{MR}^*}$, $\pi_s^{\mathrm{TR}^*} > \pi_s^{\mathrm{RR}^*} > \pi_s^{\mathrm{MR}^*}$.
Where, $f_2(\gamma,\theta)$ and $f_3(\gamma,\theta)$ are a binary function related to γ and θ, and makes $\pi_m^{\mathrm{MR}^*} = \pi_m^{\mathrm{TR}^*}$ and $\pi_r^{\mathrm{RR}^*} = \pi_r^{\mathrm{TR}^*}$ respectively.

Different from the results of manufacturer as the service design provider, we find more interesting conclusions in Conclusion 5.4. The manufacturer and retailer are not always more profitable under their own led channel structures. Under certain conditions, the recycler-led channel structure may be more favorable to the profit acquisition of manufacturer and retailer. This condition can be converted into a binary function related to the consumers' preference degree of γ and θ for ecological design and service design level. And for the recycler and the whole system, both of them can obtain greater profits under the recycler-led channel structure, which is consistent with the results in Conclusion 5.2. Our analysis finds that the superior channel structure led by the manufacturer or retailer mainly depends on the trade-off between the value-cost ratio of manufacturer's investment in ecological design and the value-cost ratio of retailer's investment in service design.

5.2. Comparative analysis of service design providers

This section will further explore how the change of service design provider will affect the equilibrium strategy and profit of each CLSC member under three channel structures in which manufacturer-led Stackelberg, retailer-led Stackelberg and recycler-led Stackelberg.

Conclusion 5.5. By comparing the equilibrium results, and the profit of each member and the whole system in model MM and MR under the manufacture-led channel structure, we can get:

(a) $p^{\mathrm{MR}^*} < p^{\mathrm{MM}^*}$, $g^{\mathrm{MR}^*} > g^{\mathrm{MM}^*}$, $s_r^{\mathrm{MR}^*} > s_m^{\mathrm{MM}^*}$, $q^{\mathrm{MR}^*} > q^{\mathrm{MM}^*}$, $\tau_t^{\mathrm{MR}^*} > \tau_t^{\mathrm{MM}^*}$;
(b) $\pi_m^{\mathrm{MR}^*} > \pi_m^{\mathrm{MM}^*}$, $\pi_r^{\mathrm{MR}^*} > \pi_r^{\mathrm{MM}^*}$, $\pi_t^{\mathrm{MR}^*} > \pi_t^{\mathrm{MM}^*}$, $\pi_s^{\mathrm{MR}^*} > \pi_s^{\mathrm{MM}^*}$.

Conclusion 5.5 discusses the selection of service design providers in the manufacturer-led CLSC. Compared with the manufacturer, the selling price is lower when the service design is carried out by the retailer, and the ecological design level and service design level of the whole CLSC are relatively higher. Meanwhile, the retailer as the service design provider is also conducive to improving consumer demand and recycling efficiency of waste products. Further, we find that each member and the whole system are more profitable when the retailer as the service design provider. Thus, it is a superior strategy for the CLSC led by the manufacturer to have the downstream retailer act as the service design provider.

Conclusion 5.6. By comparing the equilibrium results, and the profit of each member and the whole system in model RM and RR under the retailer-led channel structure, we can get:

(a) $p^{\mathrm{RM}^*} < p^{\mathrm{RR}^*}$, $g^{\mathrm{RM}^*} > g^{\mathrm{RR}^*}$, $s_m^{\mathrm{RM}^*} > s_r^{\mathrm{RR}^*}$, $q^{\mathrm{RM}^*} > q^{\mathrm{RR}^*}$, $\tau_t^{\mathrm{RM}^*} > \tau_t^{\mathrm{RR}^*}$;
(b) $\pi_m^{\mathrm{RM}^*} > \pi_m^{\mathrm{RR}^*}$, $\pi_r^{\mathrm{RM}^*} > \pi_r^{\mathrm{RR}^*}$, $\pi_t^{\mathrm{RM}^*} > \pi_t^{\mathrm{RR}^*}$, $\pi_s^{\mathrm{RM}^*} > \pi_s^{\mathrm{RR}^*}$.

The analysis result of Conclusion 5.6 finds that when the retailer acts as the channel leader, the service design conducted by the upstream manufacturer is more conducive to the CLSC to obtain a lower selling price and a higher ecological design and service design level. In addition, consumer demand and the recycling efficiency have been significantly improved. Following this logic, each CLSC member and the whole system gain more profit when the manufacturer as the service design provider. Compared with Conclusion 5.5, in a retailer-led CLSC, it is a dominant strategy for the upstream manufacturer to invest in service design.

Conclusion 5.7. By comparing the equilibrium results, and the profit of each member and the whole system in model TM and TR under the recycler-led channel structure, we can get:

(a) $p^{\mathrm{TM}^*} = p^{\mathrm{TR}^*}$, $g^{\mathrm{TM}^*} = g^{\mathrm{TR}^*}$, $s_m^{\mathrm{TM}^*} = s_r^{\mathrm{TR}^*}$, $q^{\mathrm{TM}^*} = q^{\mathrm{TR}^*}$, $\tau_t^{\mathrm{TM}^*} = \tau_t^{\mathrm{TR}^*}$;
(b) $\pi_m^{\mathrm{TR}^*} > \pi_m^{\mathrm{TM}^*}$, $\pi_r^{\mathrm{TM}^*} > \pi_r^{\mathrm{TR}^*}$, $\pi_t^{\mathrm{TM}^*} = \pi_t^{\mathrm{TR}^*}$, $\pi_s^{\mathrm{TM}^*} = \pi_s^{\mathrm{TR}^*}$.

Different from the case of the manufacturer-led and retailer-led channel structure, the study of Conclusion 5.7 shows that, for any service design provider, the selling price, ecological design level and service design level of the whole CLSC are always the same. Meanwhile, the consumer demand and the recycling efforts level are also the same. This is because, in the recycler-led CLSC, the decision positions of the manufacturer and the retailer are equal in the supply chain, and they determine their own decision variables at the same time. Therefore, the change of service design provider will not affect their final decision, and thus will not lead to a change in the consumer demand and the recycling efforts level. Interestingly, the results show that when the retailer is a service design provider, the manufacturer makes more profits, and when the manufacturer is a service design provider, the retailer makes more profits, the recycler and the whole system make the same profit in both cases. This also reveals that under the recycler-led channel structure, the change of service design provider only makes the revenue transfer between the manufacturer and retailer, but will not have an impact on the recycler and the whole system.

According to the results of Conclusions 5.5–5.7, in terms of the most beneficial to the sustainable development of the whole CLSC, when the manufacturer (retailer) acts as the channel leader, it is more favorable for the retailer (manufacturer) to provide service design. However, when the recycler is the leader, the change of service design provider will not affect the final profit of the whole closed loop supply chain. Thus, the difference of leadership structure is a direct factor affecting the selection of the optimal service design provider. So, the channel leader should undertake the work of controlling and coordinating the supply chain, which not only encourages the follower to take the initiative to undertake the service design, but also ensures the reasonable profit and development of the follower, so as to effectively improve the operational efficiency of the CLSC, to maximize the benefits of the supply chain members and the whole system.

Conclusion 5.8. By comparing the profit of each member under different leadership channel structures and service design providers, we can get:

(a) When the manufacturer act as the channel leader, $\pi_m^{\mathrm{MM}^*} > \pi_r^{\mathrm{MM}^*} > \pi_t^{\mathrm{MM}^*}$, $\pi_m^{\mathrm{MR}^*} > \pi_r^{\mathrm{MR}^*} > \pi_t^{\mathrm{MR}^*}$;
(b) When the retailer act as the channel leader, $\pi_r^{\mathrm{RM}^*} > \pi_m^{\mathrm{RM}^*} > \pi_t^{\mathrm{RM}^*}$, $\pi_r^{\mathrm{RR}^*} > \pi_m^{\mathrm{RR}^*} > \pi_t^{\mathrm{RR}^*}$;
(c) When the recycler act as the channel leader, $\pi_r^{\mathrm{TM}^*} > \pi_m^{\mathrm{TM}^*} > \pi_t^{\mathrm{TM}^*}$; if $\frac{\gamma^2}{\delta} \leq \frac{\theta^2}{\eta}$, $\pi_r^{\mathrm{TR}^*} \geq \pi_m^{\mathrm{TR}^*} > \pi_t^{\mathrm{TR}^*}$, if $\frac{\gamma^2}{\delta} > \frac{\theta^2}{\eta}$, then, $\pi_m^{\mathrm{TR}^*} > \pi_r^{\mathrm{TR}^*} > \pi_t^{\mathrm{TR}^*}$.

The study of Conclusion 5.8 shows that in the case of the manufacturer-led or retailer-ed, for any given service design provider, the leader can always obtain more profit than other members, and the recycler's profit is always the lowest. When the recycler act as the channel leader, compared with other leadership structures, although the recycler's profit is greatly increased, it is still smaller than that of the manufacturer and retailer. Further comparing the profit between manufacturer and retailer, it is found that the size of their profit depends on who provides service design: if the manufacturer is the service design provider, the retailer always gains more profit than the manufacturer; if the retailer is the service design provider, the value cost ratio brought by the manufacturer through ecological design is higher than the value cost ratio generated by the retailer through service design, then the retailer will gain more profit. On the contrary, the manufacturer always gains more profit than the retailer.

6. Numerical simulation

In this section, using numerical examples, we prove the correctness of the above theoretical research conclusions and analyse the impact of consumers' sensitivity θ and γ to the ecological design and service design level on the CLSC equilibrium results and members' profits in different decision models. After considering the practical significance of the model comprehensively and comparing with the relevant literature, selection of initial simulation data after certain processing is as follows: we set $a = 500$, $k = 1500$ by referring to the example of Savaskan *et al.* [3]. According to the problem description and model assumptions, the unit cost of using raw materials is higher than the unit remanufacturing cost of using waste products. We refer to Luo *et al.* [64], $c_m = 40$, $c_r = 10$, so $\Delta = c_m - c_r = 30$, to ensure that the manufacturer can make a profit by recycling and remanufacturing (*i.e.*, $\Delta - b > 0$), so we set $b = 10$. In addition, owing to the high investment cost coefficient of ecological design and service design, we refer to Juhong *et al.* [63], and we set $\eta = 180$, $\delta = 220$. Finally, since consumers are highly sensitive to product price, we assume $\beta = 6$. Because consumers' sensitivity to the ecological design level γ and service design level θ is significantly different, and may be lower or higher than β, we assume that the values of γ and θ are 1, 4 and 8 during the analysis process. The specific simulation results are shown in Tables 2, 3, Figures 2 and 3.

Table 2 shows the impact of parameters γ and θ on the equilibrium results of CLSC under three leadership structures when the manufacturer provides service design. First, from the vertical view of Table 2, when θ is constant, the eco-design level invested by the manufacturer will increase with γ under any leadership structure, thus catering to the green preference of consumers. We also find that the increase of γ can enhance of the manufacturer' service design level. Second, from the horizontal view of Table 2, when γ is constant, the increase of θ enhances the manufacturer' service design level, no matter under what kind of leadership structure, so as to cater to consumers' preference for a high service level. By the same logic, the increase of θ improves of the manufacturer's ecological design level. Therefore, we can prove that when the CLSC invests in both ecological design and service design, they play a synergistic role in promoting each other. An increase in the level of ecological and service designs raise the manufacturer's production cost. Interestingly, through Table 2, we find that consumer demand is not reduced, which indicates that consumers are willing to pay a corresponding premium for products with environmental benefits and good service guarantee. In addition, the numerical example is also used to verify that "when the manufacturer acts as the service design provider, the recycler-led Stackelberg mode is the most favourable to the equilibrium strategy of the CLSC" in Conclusion 5.1.

TABLE 2. Equilibrium results changes with γ and θ under three leadership structures when the manufacturer as the service design provider.

	Parameter	$L=$ MM			$L=$ RM			$L=$ TM		
		θ								
Decision	γ	1	4	8	1	4	8	1	4	8
w^{ij*}	1	56.26	56.33	56.56	48.13	48.20	48.44	49.20	49.24	49.39
	4	56.32	56.39	56.62	48.19	48.26	48.50	49.24	49.28	49.43
	8	56.50	56.58	56.82	48.38	48.46	48.71	49.36	49.41	49.56
p^{ij*}	1	69.81	69.94	70.36	69.80	69.87	70.11	66.28	66.42	66.89
	4	69.91	70.04	70.47	69.86	69.93	70.17	66.40	66.54	67.01
	8	70.26	70.39	70.83	70.05	70.13	70.38	66.78	66.92	67.41
g^{ij*}	1	0.0616	0.0619	0.0627	0.0616	0.0622	0.0640	0.0776	0.0781	0.0795
	4	0.2472	0.2483	0.2518	0.2482	0.2504	0.2577	0.3120	0.3138	0.3196
	8	0.5001	0.5024	0.5096	0.5081	0.5127	0.5280	0.6334	0.6370	0.6490
s^{ij*}	1	0.0753	0.3024	0.6134	0.0753	0.3039	0.6253	0.0949	0.3817	0.7775
	4	0.0755	0.3035	0.6156	0.0758	0.3061	0.6300	0.0953	0.3835	0.7812
	8	0.0764	0.3070	0.6228	0.0776	0.3133	0.6453	0.0968	0.3893	0.7932
q^{ij*}	1	81.29	81.65	82.80	81.34	82.05	84.42	102.49	103.07	104.97
	4	81.58	81.94	83.10	81.92	82.64	85.04	102.97	103.55	105.46
	8	82.52	82.89	84.08	83.84	84.60	87.12	104.51	105.11	107.08
τ^{ij*}	1	0.2710	0.2722	0.2760	0.2711	0.2735	0.2814	0.3942	0.3967	0.4050
	4	0.2719	0.2731	0.2770	0.2731	0.2755	0.2835	0.3963	0.3988	0.4071
	8	0.2758	0.2763	0.2803	0.2795	0.2820	0.2904	0.4030	0.4056	0.4142

TABLE 3. Equilibrium results changes with γ and θ under three leadership structures when the retailer as the service design provider.

	Parameter	$L=$ MR			$L=$ RR			$L=$ TR		
		θ								
Decision	γ	1	4	8	1	4	8	1	4	8
w^{ij*}	1	56.25	56.20	56.05	48.13	48.17	48.28	49.20	49.24	49.39
	4	56.31	56.26	56.11	48.19	48.23	48.34	49.24	49.28	49.43
	8	56.50	56.45	56.30	48.38	48.42	48.54	49.36	49.41	49.56
p^{ij*}	1	69.80	69.87	70.11	69.80	69.93	70.36	66.28	66.42	66.89
	4	69.91	69.98	70.22	69.86	69.99	70.42	66.40	66.54	67.01
	8	70.26	70.33	70.59	70.05	70.19	70.63	66.78	66.92	67.41
g^{ij*}	1	0.0616	0.0621	0.0639	0.0616	0.0619	0.0627	0.0776	0.0781	0.0795
	4	0.2473	0.2495	0.2567	0.2482	0.2493	0.2528	0.3120	0.3138	0.3196
	8	0.5003	0.5047	0.5195	0.5080	0.5102	0.5177	0.6334	0.6370	0.6490
s^{ij*}	1	0.0753	0.3038	0.6252	0.0753	0.3025	0.6135	0.0949	0.3817	0.7775
	4	0.0756	0.3049	0.6275	0.0758	0.3046	0.6180	0.0953	0.3835	0.7812
	8	0.0764	0.3085	0.6350	0.0776	0.3118	0.6327	0.0968	0.3893	0.7932
q^{ij*}	1	81.32	82.03	84.40	81.31	81.67	82.82	102.49	103.07	104.97
	4	81.61	82.32	84.71	81.89	82.25	83.43	102.97	103.55	105.46
	8	82.55	83.28	85.72	83.81	84.19	85.42	104.51	105.11	107.08
τ^{ij*}	1	0.2711	0.2734	0.2813	0.2710	0.2722	0.2761	0.3942	0.3967	0.4050
	4	0.2720	0.2744	0.2824	0.2730	0.2742	0.2781	0.3963	0.3988	0.4071
	8	0.2752	0.2776	0.2857	0.2794	0.2806	0.2847	0.4030	0.4056	0.4142

Table 3 shows that, when retailer provides service design, the impact of γ and θ on the equilibrium results of CLSC under three leadership structures. Similar to the analysis results in Table 2, no matter under any leadership structure, the increase of γ and θ can raise the ecological design level and service design level of the system, and also conducive to the expansion of consumer demand and the improvement of recycling efficiency. Then, according to the data in Tables 2 and 3, when the leadership channel structure is fixed, we compare the equilibrium results of the two service design providers, and it can be seen that the difference of leadership channel structure is the decisive factor affecting the selection of the best service design provider in the CLSC. Specifically, for the overall operational efficiency of the CLSC, under the manufacturer-led channel structure, retailer provides service design is the dominant strategy. Under the retailer-led channel structure, the manufacturer to provide service design is the dominant strategy; Under the recycler-led channel structure, the investment effect of manufacturer and retailer is the same. This again verified the results of Conclusions 5.5–5.7.

Through the observation of Figure 2, the increase of γ and θ can boost the profits of members and the whole system under whatever leadership channel structure. This also reveals that with the enhancement of consumers' awareness of green environmental protection and the improvement of service level requirements, the CLSC should increase the investment level of efficiency of ecological design and service design. On the one hand, it can boost the profits of member, and achieve a green and sustainable development mode of reducing CO2e. Secondly, we compare the profit of each member and the whole system under the three leadership structures. For the manufacturer, its profit is always the largest under its own leadership channel structure and the smallest under the leadership of retailer. However, the recycler and the whole system always get the maximum profit under the recycler-led, and the minimum profit under the manufacturer-led. However, for the retailer, it is not always under its own leadership structure to obtain more profit, and sometimes the recycler-led Stackelberg mode is better for the retailer to obtain profit. The simulation result is also a further verification of Conclusion 5.2.

Figure 3 shows the impact of γ and θ on the profits of members and the system under the three leadership structures when the retailer provides service design. It can be seen from the figure that the recycler and the whole system still make more profit under the recycler-led, which is consistent with the results shown in Figure 2. However, we can see that the retailer-led channel structure is not always better than that manufacturer-led at this time, which mainly depends on the trade-off between the value cost ratio of manufacturer's investment in ecological design and the value cost ratio of retailer's investment in service design. In addition, the manufacturer and retailer do not always get more profit under their own leadership structure. Under certain conditions, the recycler-led channel structure may be more favorable for the profits of manufacturer and retailer, corresponding to the situation that the consumer's preference for service design exceeds 6.3 and the consumer's preference for ecological design exceeds 7.1 respectively. The results further validate the research results in Conclusion 5.4.

7. Discussion and implications

7.1. Results and discussion

Based on the importance of CLSC management in the implementation of product lifecycle management in enterprises and the open question of different leadership and service design provider selection in CLSC, this paper studies multiple CLSC decision models employing three different leadership structures (*i.e.*, manufacturer-led, retailer-led and recycler-led) and two service design providers (manufacturer and retailer). We give the optimal operational decision of the supply chain system under different scenarios and clarify the optimal selection strategy of leadership structure and service design providers. Next, we answer and discuss the main research questions of this paper.

This paper first answers the question about the impact of adopting ecological design and service design in CLSC system operation. In terms of product demand and recycling efficiency, we find that under the manufacturer-led structure, ecological design is always conducive to expanding market demand and improving recycling efforts level of the recycler. This conclusion was confirmed in study of Chai *et al.* [40]. Furthermore, based on the research of Chai *et al.* [40], we extend the supply chain to the structure of manufacturer-led,

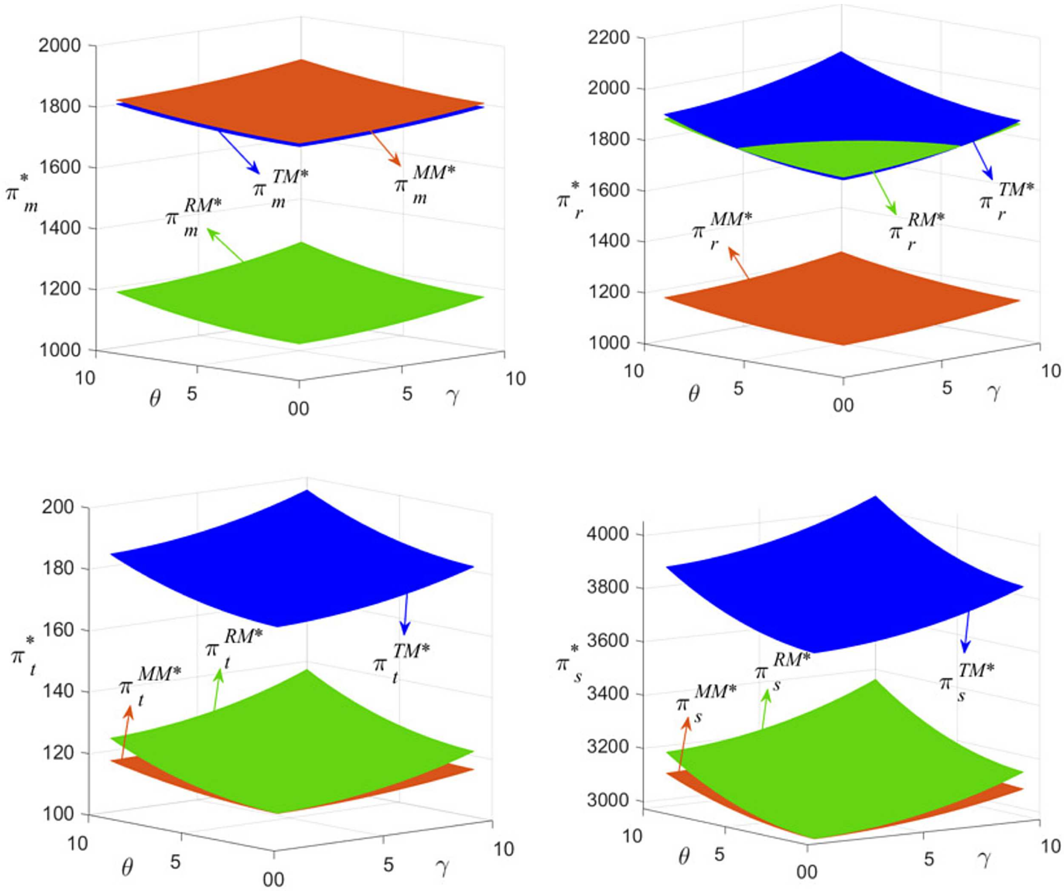

FIGURE 2. The profit of each member and the whole system changes with γ and θ under three leadership structures when the manufacturer as the service design provider.

retailer-led and recycler-led, and introduce the service designs of manufacturer and retailer. Thereby, we produce a new finding, that is, regardless of the leadership structure or who the service design provider might be, the adoption of ecological design and service design simultaneously not only further expands the market demand for products and the recycling effort level of the recycler but also promotes the increase of profits for each member and the whole system. This notable conclusion is also supported by the literature, such as Liu *et al.* [41] and Kong *et al.* [46], whose research found that ecological design and service design are effective in promoting the sustainable operation of the CLSC system.

When the manufacturer and retailer respectively act as the service design provider, we systematically compare the advantages and disadvantages of the three leadership structures and give the conditions for different subjects to choose the optimal leadership structure. First, we find an interesting conclusion when comparing the impact of the three leadership structures on system operation efficiency and total profit, which is different from our intuition. That is, compared with the manufacturer-led and retailer-led structure, the recycler-led structure is always the optimal structure to promote sustainable operation of the system. Through comparative analysis of the equilibrium results presented in Section 5, we conclude that under the recycler-led structure, market demand is the largest and recycling effort level is the highest. Second, the manufacturer and retailer have the highest ecological design level and service design level while the market demand increases. This conclusion was

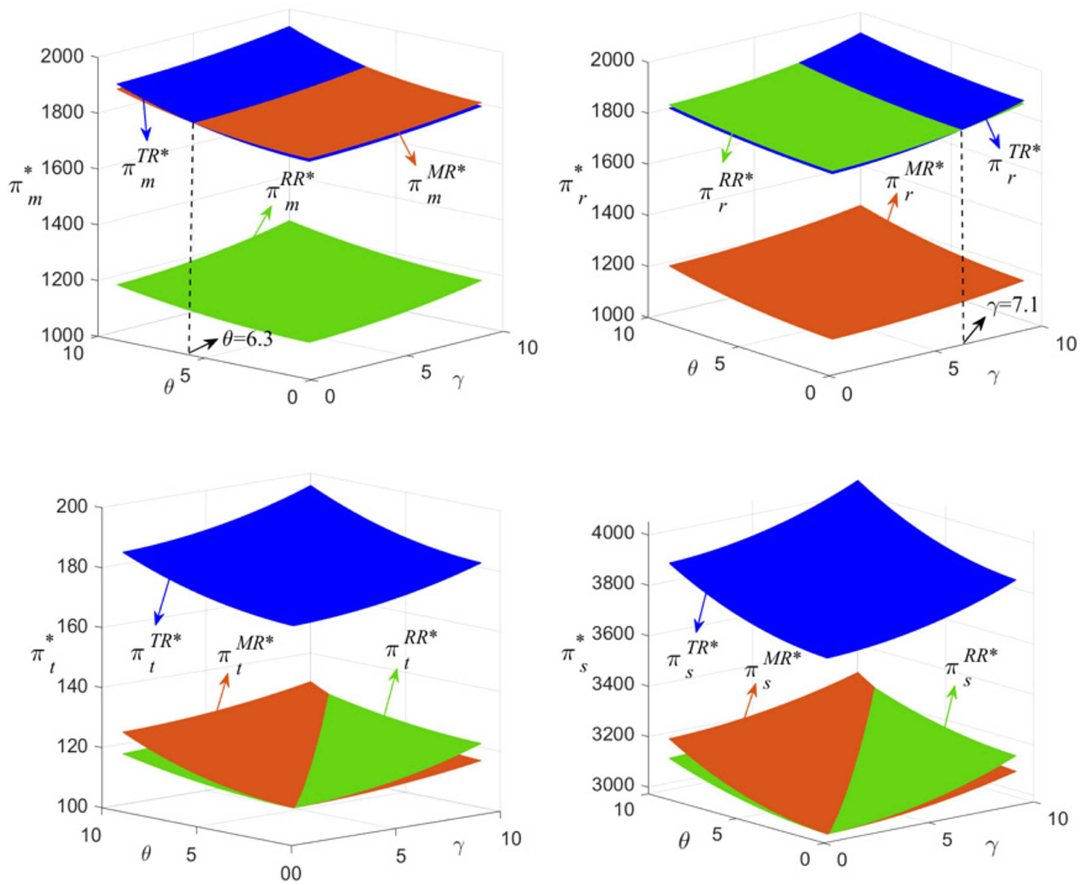

FIGURE 3. The profit of each member and the whole system changes with γ and θ under three leadership structures when the retailer as the service design provider.

also confirmed in the study of Jafari *et al.* [65], that is, when the recycler has the priority to make decision, other members benefit. In addition, the conditions for different members to choose the optimal leadership structure are different. Specifically, the recycler always obtains the highest profit under the structure led by itself. The manufacturer and retailer may be more conducive to their profit growth under recycler-led structure, rather than the structure led by themselves, which mainly depends on consumer preference of ecological design and service design level. Therefore, we answer the second research question presented in the introduction, that is, under the recycler-led structure, the forward and reverse sustainable operation efficiency of the system is the highest, and the ecological design level and service design level is the highest, which is conducive to the sustainable operation of the whole system.

When the manufacturer, the retailer and the recycler act as the channel leader respectively, we analyse the optimal selection strategy of the service design provider in CLSC. The results show that the leadership structure is an important factor affecting the selection of the optimal service design provider. From the perspective of system operation efficiency and member profit maximisation, we find that when the retailer acts as channel leader, it is a dominant strategy for the manufacturer to provide service design, that is, it is a dominant strategy for the manufacturer to provide simultaneously ecological design and service design, which is consistent with the study in Shi *et al.* [20]. In addition, this paper also considers the manufacturer-led and recycler-led structure, and we find that when the manufacturer acts as the channel leader, the retailer service design is the dominant strategy. When the recycler acts as the leader, no matter whether the manufacturer or the retailer acts as the service design provider, the effect is the same on the system. That is to say, the change of service design provider causes only the internal transfer of revenue between the manufacturer and the retailer; it does not affect the recycler and the overall operation of the system. This thought-provoking finding provides a reference for the choice of channel leadership and service design provider in CLSC.

7.2. Management implications

In this paper, we present the optimal operational decisions for the CLSC system from the perspective of the life cycle. The logical relationship between ecological design in production, service design in use, recycling at the end of life, channel leadership structure and CLSC operation is presented, and the optimal channel leadership structure selection strategy is determined. Establishing a new sustainable CLSC management system has theoretical and practical significance. Further, from the perspective of policymakers and supply chain members, some specific suggestions and implementation schemes are given below, so that the CLSC system can operate more efficiently.

7.2.1. Policy maker

As a national and regional policymaker, the government's role in regulating and mediating the supply chain system has been widely recognised in the literature [13, 28]. First, based on incentive theory, and considering the promotion effect of subsidies on enterprise behaviour, this paper suggests that the government implement financial subsidy incentive policies for manufacturers and retailers. We suggest that the government establish a progressive subsidy according to the level of ecological design and service design of enterprise, that is, the higher the ecological design level and service design level, the higher the subsidy level. The reason behind this recommendation is that the capital subsidy conforms to the "rational economic man" assumption of the decision-makers [35]. Moreover, the research demonstrates that the ecological design and service design of the manufacturer and retailer can effectively improve the green degree of products and the recycling rate of waste products, which can in turn improve the positive effect of the system on the environment. However, due to the high cost of ecological design and service design, over-investment will increase the investment risk of investors and inhibit their investment level, although subsidies can effectively alleviate these concerns.

Second, studies have shown that the combination of regulation and subsidy is more effective than a single subsidy policy [15]. Therefore, this paper suggests that the government implement subsidy-supporting policies. For example, the government could adopt a subsidy policy in the form of progressive compensation of regulation, that is, setting regulatory standards for ecological design and service design and providing subsidies to the enterprise that meet the standards. In addition, considering the insufficient information transfer between the government and the enterprise, and the difficult measurement of subsidy effect, we suggest that the government adopt public information platforms and public supervision to supervise the ecological design and service design level of enterprises.

Finally, we recommend that the government formulate a guidance strategy to support the enterprise to implement ecological design and service design actively. Research shows that an increase in consumers' preference for green products is conducive to improving the green design of the manufacturing enterprise [36]. Therefore, this paper suggests that the government facilitate green education for consumers through public education and news media to improve consumer awareness of green product purchase. This could also improve the ecological design of the enterprise and improve the sustainable development of CLSC.

7.2.2. Supply chain members

As decision-makers, supply chain members' behaviour directly affects the resilience and development direction of the supply chain system. Therefore, this section offers some management suggestions from the perspective of supply chain members.

First, in terms of the whole system, our study shows that the manufacturer or retailer is not the best candidate for the channel leader; if the recycler acts as the leader, this will produce a better result. This finding is important because it provides new scientific evidence to support the idea of shifting channel leadership from the upstream manufacturer or retailer to the downstream recycler in the CLSC. Therefore, this paper suggests that the manufacturer and retailer should support a recycler-led CLSC system. In addition, considering the differences in behaviour and decision-making between each member, we suggest that members establish an information-sharing mechanism [39] and a big data information-sharing platform [16], which would be helpful for improving the information processing ability of the CLSC system and reducing the uncertain results caused by information delay.

Second, in terms of the ecological design provider, as the upper decision-maker of the CLSC system, the manufacturer's ecological design directly affects carbon reduction in the process of product production and remanufacturing. It is also the role of the enterprise to fulfil its social responsibility actively, and previous studies have shown that the social responsibility behaviour has a strong market expansion effect [4, 20]. Therefore, we suggest that the manufacturer actively adopt ecological design, that is, the enterprise designs and produces products from the perspectives of social, environmental and economic sustainable development. In addition, green investment can benefit other members of the supply chain, which has also been confirmed in the literature [36]. However, the high investment cost will limit the manufacturer's ecological design level. Therefore, we suggest that the retailer and recycler actively share the manufacturer's ecological design cost [38], which can also realise the Pareto improvement of the CLSC system.

Finally, in terms of service design provider, although our study found that when the recycler acts as the channel leader, whether the manufacturer or the retailer acts as the service design provider will produce the same effect for the whole system. However, in the process of implementing service design, the provider will incur corresponding service design costs. Therefore, this paper suggests that the manufacturer and the retailer should actively implement the service design, and a win–win situation of both members can be achieved by signing a service design cost-sharing and revenue sharing contract [46, 48], which is helpful for solving channel conflict and realise Pareto improvement.

8. Conclusions

The different channel leadership structures and change of service design providers are important factors that affect the optimal decision and profit distribution of supply chain members. Hence, this paper considers three leadership structures, namely, manufacturer-led, retailer-led and recycler-led, and two service design providers, namely, manufacturer and retailer, and gives the equilibrium strategies of leader and subordinator under six combinations. The channel performance of the supply chain between three different leadership structures and the advantages and disadvantages of two different service design providers are systematically compared. Specifically, we draw the following important conclusions.

(1) No matter in what kind of decision situation, supply chain members to take the ecological design and service design is always conducive to an increase in product market demand and level of recycling effort, as well as an increase in the profit of members and the system. This is because the adoption of ecological design and service design of members directly affects the level of CO2e reduction and service quality in the product use stage. Therefore, consumers are willing to pay higher prices for products with green and good services. (2) The recycler-led channel structure is always superior to the traditional mode led by manufacturer or retailer. That is to say, different service design providers will not affect the performance of the optimal leadership structure. Previous studies on CLSC management mostly assume that manufacturer or retailer has dominant bargaining power, because manufacturer and retailer usually play a very influential role in the CLSC. However, this study demonstrates that no matter who provides the service design, the manufacturer or retailer is not the best leader of the system; contrarily, the recycler, as the channel leader, can deliver the best results to the system. (3) Further comparing channel performance between the manufacturer-led and retailer-led channel structures, our study shows that different service design providers will affect the performance of the original leadership structure. Specifically, if the manufacturer is the service design provider, the retailer-led channel structure is always superior, which is consistent with previous research results [29]. If the retailer acts as the service design

provider, it will be weighed by the value-cost ratio between ecological design and service design, this is a new finding. (4) The difference in channel leadership structure is an important factor influencing the service design provider selection of CLSC system. Specifically, under the manufacturer-led channel structure, it is a dominant strategy for the retailer to be the service design provider of the system. Under the retailer-led channel structure, it is better for manufacturer to provide service design for the system. However, under the recycler-led channel structure, it brings the same effect to the system whether the manufacturer or the retailer acts as the service design provider.

Although our model is fully supported by the literature and some research results have been obtained, many directions are worth further exploration in future research. First, our research was completed under the condition that the market demand is determined. However, in actuality, market demand is often difficult to predict and fluctuates owing to disturbance of various factors. Therefore, it would be useful to consider the performance of different channel leadership structures and the selection of service design providers under the condition of market demand uncertainty. Second, we assume that supply chain members do not experience capital budget constraints in the innovation investment process of adopting ecological design and service design. However, in reality, a limited investment budget may cause difficulties achieving the optimal investment level, which would affect our conclusion. Finally, we use game theory modelling to analyse the interaction between different channel leadership and service design providers. In future research, it would be productive to consider using empirical research methods to test the relationship between market leadership and service design provider selection. This would render the research results more reliable and convincing.

Appendix A.

Proof of Proposition 4.1. First, by calculating the second order partial derivatives of the retailer's profit function $\pi_r^{\mathrm{MM}}(p)$ and the recycler's profit function $\pi_t^{\mathrm{MM}}(\tau_t)$ with respect to their respective decision variables p^{MM} and τ_t^{MM}, we can get $\frac{\partial^2\pi_r^{\mathrm{MM}}(p)}{\partial p^2} = -2\beta < 0$, $\frac{\partial^2\pi_t^{\mathrm{MM}}(\tau_t)}{\partial \tau_t^2} = -2k < 0$, that is, the profit functions of retailer and recycler are strictly concave functions with respect to p^{MM} and τ_t^{MM}, so there is a unique optimal solution, according to the first-order conditions, the optimal response functions of retailer and recycler can be obtained as $p^{\mathrm{MM}}(w,g,s_m) = \frac{a+\beta w+\gamma g+\theta s_m}{2\beta}$ and $\tau_t^{\mathrm{MM}}(w,g,s_m) = \frac{b(a-\beta w+\gamma g+\theta s_m)}{4k}$. Then, by substituting $p^{\mathrm{MM}}(w,g,s_m)$ and $\tau_t^{\mathrm{MM}}(w,g,s_m)$ into formula (4.2), it is easy to verify that the manufacturer's profit function $\pi_m^{\mathrm{MM}}(w,g,s_m)$ is a joint concave function with respect to its decision variables w^{MM}, g^{MM} and s_m^{MM}. According to the first-order conditions, the manufacturer's optimal wholesale price w^{MM^*}, the optimal ecological design level g^{MM^*} and service design level $s_m^{\mathrm{MM}^*}$ can be obtained. Furthermore, by substituting w^{MM^*}, g^{MM^*} and $s_m^{\mathrm{MM}^*}$ into the optimal response functions $p^{\mathrm{MM}}(w,g,s_m)$ and $\tau_t^{\mathrm{MM}}(w,g,s_m)$ to obtain the optimal selling price p^{MM^*} and the optimal recycling effort level $\tau_t^{\mathrm{MM}^*}$. According to formula (4.1), the corresponding consumer demand q^{MM^*} can be obtained. Finally, the above equilibrium results are substituted into formula (4.2)–(4.4) in turn, that is, the manufacturer's profit $\pi_m^{\mathrm{MM}^*}$, retailer's profit $\pi_r^{\mathrm{MM}^*}$, recycler's profit $\pi_t^{\mathrm{MM}^*}$ and the whole system's profit $\pi_s^{\mathrm{MM}^*}$ are calculated. Proposition 4.1 is proved. □

Proof of Proposition 4.2. First, let $p^{\mathrm{RM}} = w^{\mathrm{RM}} + m^{\mathrm{RM}}$, where m^{RM} is the unit profit obtained by the retailer when selling a product, and substitute $p^{\mathrm{RM}} = w^{\mathrm{RM}} + m^{\mathrm{RM}}$ into formula (4.2) and (4.4), and calculate the second partial derivatives of the manufacturer's profit function $\pi_m^{\mathrm{RM}}(w,g,s_m)$ and the recycler's profit function $\pi_t^{\mathrm{RM}}(\tau_t)$ with respect to their respective decision variables. It is not difficult to verify that $\pi_m^{\mathrm{RM}}(w,g,s_m)$ is joint concave function about w^{RM}, g^{RM} and s_m^{RM}. $\pi_t^{\mathrm{RM}}(\tau_t)$ is strictly concave function with respect to τ_t^{RM}. Therefore, formula (4.2) and (4.4) both have the optimal solutions. According to the first-order condition, the optimal response functions of manufacturer and recycler are $w^{\mathrm{RM}}(m) = \frac{2kc_m(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta(2k-\beta b(\Delta-b))(a-\beta m)}{2k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b))}$, $g^{\mathrm{RM}}(m) = \frac{2k\eta\gamma(a-\beta c_m-\beta m)}{2k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b))}$, $s_m^{\mathrm{RM}}(m) = \frac{2k\delta\theta(a-\beta c_m-\beta m)}{2k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b))}$, $\tau_t^{\mathrm{RM}}(m) = \frac{b\eta\delta\beta(a-\beta c_m-\beta m)}{2k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b))}$. Substitute $w^{\mathrm{RM}}(m)$, $g^{\mathrm{RM}}(m)$, $s_m^{\mathrm{RM}}(m)$ and $\tau_t^{\mathrm{RM}}(m)$ into formula (4.3) respectively, and it is easy to prove that the profit function $\pi_r^{\mathrm{RM}}(m)$

of the retailer is a strictly concave function with respect to its decision variable m^{RM}. According to the first-order condition, the maximum unit profit of the retailer can be obtained as $m^{\mathrm{RM}^*} = \frac{a-\beta c_m}{2\beta}$. Furthermore, by substituting m^{RM^*} into the optimal response functions $w^{\mathrm{RM}}(m)$, $g^{\mathrm{RM}}(m)$, $s_m^{\mathrm{RM}}(m)$ and $\tau_t^{\mathrm{RM}}(m)$, the optimal wholesale price w^{RM^*}, the optimal ecological design level g^{RM^*}, the service design level $s_m^{\mathrm{RM}^*}$ and the optimal recycling effort level $\tau_t^{\mathrm{RM}^*}$ can be obtained. Then, according to $p^{\mathrm{RM}} = w^{\mathrm{RM}} + m^{\mathrm{RM}}$ and formula (4.1), the optimal selling price p^{RM^*} and corresponding consumer demand q^{RM^*} can be obtained. Finally, the above equilibrium results are substituted into formula (4.2)–(4.4), that is, the manufacturer's profit $\pi_m^{\mathrm{RM}^*}$, retailer's profit $\pi_r^{\mathrm{RM}^*}$, recycler's profit $\pi_t^{\mathrm{RM}^*}$ and the whole system's profit $\pi_s^{\mathrm{RM}^*}$ can be obtained. Proposition 4.2 is proved. □

Proof of Proposition 4.3. First, let $p^{\mathrm{TM}} = w^{\mathrm{TM}} + m^{\mathrm{TM}}$, where m^{TM} is the unit profit obtained by the retailer when selling a product, and substitute $p^{\mathrm{TM}} = w^{\mathrm{TM}} + m^{\mathrm{TM}}$ into formula (4.2) and (4.3), and calculate the second partial derivatives of the manufacturer's profit function $\pi_m^{\mathrm{TM}}(w, g, s_m)$ and the retailer's profit function $\pi_r^{\mathrm{TM}}(m)$ with respect to their respective decision variables. It is not difficult to verify that $\pi_m^{\mathrm{TM}}(w, g, s_m)$ is joint concave function about w^{TM}, g^{TM} and s_m^{TM}. $\pi_r^{\mathrm{TM}}(m)$ is strictly concave function with respect to m^{TM}. Therefore, formula (4.2) and (4.3) both have the optimal solutions. According to the first-order conditions, the optimal response functions of manufacturer and retailer about τ_t^{TM} are $w^{\mathrm{TM}}(\tau_t) = \frac{a\eta\delta + (c_m + (\Delta - b)\tau_t)(2\eta\delta\beta - \delta\theta^2 - \eta\gamma^2)}{3\eta\delta\beta - \delta\theta^2 - \eta\gamma^2}$, $g^{\mathrm{TM}}(\tau_t) = \frac{\eta\gamma(a - \beta c_m + \beta\tau_t(\Delta - b))}{3\eta\delta\beta - \delta\theta^2 - \eta\gamma^2}$, $s_m^{\mathrm{TM}}(\tau_t) = \frac{\delta\theta(a - \beta c_m + \beta\tau_t(\Delta - b))}{3\eta\delta\beta - \delta\theta^2 - \eta\gamma^2}$, $m^{\mathrm{TM}}(\tau_t) = \frac{\eta\delta(a - \beta c_m + \beta\tau_t(\Delta - b))}{3\eta\delta\beta - \delta\theta^2 - \eta\gamma^2}$. Substitute $w^{\mathrm{TM}}(\tau_t)$, $g^{\mathrm{TM}}(\tau_t)$, $s_m^{\mathrm{TM}}(\tau_t)$ and $m^{\mathrm{TM}}(\tau_t)$ into formula (4.4), and it is easy to prove that the recycler's profit function $\pi_t^{\mathrm{TM}}(\tau_t)$ is a strictly concave function with respect to its decision variable τ_t^{TM}. According to the first-order condition, the recycler's optimal recycling effort level $\tau_t^{\mathrm{TM}^*}$ can be obtained. Furthermore, by substituting $\tau_t^{\mathrm{TM}^*}$ into the optimal response functions $w^{\mathrm{TM}}(\tau_t)$, $g^{\mathrm{TM}}(\tau_t)$, $s_m^{\mathrm{TM}}(\tau_t)$ and $m^{\mathrm{TM}}(\tau_t)$, the optimal wholesale price w^{TM^*}, the optimal ecological design level g^{TM^*}, the service design level $s_m^{\mathrm{TM}^*}$ and the optimal selling price $p^{\mathrm{TM}^*} = w^{\mathrm{TM}^*} + m^{\mathrm{TM}^*}$ can be obtained. Then, according to formula (4.1), can obtain the optimal consumer demand q^{TM^*}. Finally, the above equilibrium results are substituted into formula (4.2)–(4.4), that is, the manufacturer's profit $\pi_m^{\mathrm{TM}^*}$, retailer's profit $\pi_r^{\mathrm{TM}^*}$, recycler's profit $\pi_t^{\mathrm{TM}^*}$ and the whole system's profit $\pi_s^{\mathrm{TM}^*}$ can be obtained. Proposition 4.3 is proved. □

The proof process of Propositions 4.4–4.6 is similar to that of Propositions 4.1–4.3, which will not be repeated here.

Proof of Conclusion 5.1. According to the selling price in Propositions 4.1–4.3, we can get

$$
\begin{aligned}
p^{\mathrm{TM}^*} - p^{\mathrm{RM}^*} = &- \frac{k^2\left(2\beta^2\eta^2\delta^2 - \left(\delta\theta^2 + \eta\gamma^2\right)\left(4\eta\delta\beta - \delta\theta^2 - \eta\gamma^2\right)\right)\left(\eta\delta\beta - \delta\theta^2 - \eta\gamma^2\right)(a - \beta c_m)}{\beta(3\eta\delta\beta - \delta\theta^2 - \eta\gamma^2)(k(\eta\delta\beta - \delta\theta^2 - \eta\gamma^2) + \eta\delta\beta(2k - \beta b(\Delta - b)))(2k(\eta\delta\beta - \delta\theta^2 - \eta\gamma^2) + \eta\delta\beta(2k - \beta b(\Delta - b)))} \\
&- \frac{\eta\delta\beta^2\left(2\eta\delta k^2 - b(\Delta - b)\left(2k\left(\eta\delta\beta - \delta\theta^2 - \eta\gamma^2\right) + \eta\delta\beta(2k - \beta b(\Delta - b))\right)\right)\left(\eta\delta\beta - \delta\theta^2 - \eta\gamma^2\right)(a - \beta c_m)}{2\beta(3\eta\delta\beta - \delta\theta^2 - \eta\gamma^2)(k(\eta\delta\beta - \delta\theta^2 - \eta\gamma^2) + \eta\delta\beta(2k - \beta b(\Delta - b)))(2k(\eta\delta\beta - \delta\theta^2 - \eta\gamma^2) + \eta\delta\beta(2k - \beta b(\Delta - b)))} < 0, \\
p^{\mathrm{RM}^*} - p^{\mathrm{MM}^*} = &- \frac{k^2\left(\delta\theta^2 + \eta\gamma^2\right)\left(\eta\delta\beta - \delta\theta^2 - \eta\gamma^2\right)(a - \beta c_m)}{\beta(k(2\delta\eta\beta - \delta\theta^2 - \eta\gamma^2) + \eta\delta\beta(2k - \beta b(\Delta - b)))(2k(\eta\delta\beta - \delta\theta^2 - \eta\gamma^2) + \eta\delta\beta(2k - \beta b(\Delta - b)))} < 0.
\end{aligned}
$$

So, we can get $p^{\mathrm{TM}^*} < p^{\mathrm{RM}^*} < p^{\mathrm{MM}^*}$. Similarly, we can verify that $w^{\mathrm{RM}^*} < w^{\mathrm{TM}^*} < w^{\mathrm{MM}^*}$, $g^{\mathrm{TM}^*} > g^{\mathrm{RM}^*} > g^{\mathrm{MM}^*}$, $s_m^{\mathrm{TM}^*} > s_m^{\mathrm{RM}^*} > s_m^{\mathrm{MM}^*}$, $q^{\mathrm{TM}^*} > q^{\mathrm{RM}^*} > q^{\mathrm{MM}^*}$, $\tau_t^{\mathrm{TM}^*} > \tau_t^{\mathrm{RM}^*} > \tau_t^{\mathrm{MM}^*}$. Conclusion 5.1 is proved. □

Proof of Conclusion 5.2. (a) According to the manufacturer's profit in Propositions 4.1–4.3, we can get

$$
\begin{aligned}
\pi_m^{\mathrm{MM}^*} - \pi_m^{\mathrm{TM}^*} = &\ \beta^2\eta^3\delta^3(a - \beta c_m)^2 \\
&\times \left(\frac{k^3\left(\delta\theta^2 + \eta\gamma^2\right)\left(6\eta\delta\beta - \delta\theta^2 - \eta\gamma^2\right)}{(k(2\delta\eta\beta - \delta\theta^2 - \eta\gamma^2) + \eta\delta\beta(2k - \beta b(\Delta - b)))(3\eta\delta\beta - \delta\theta^2 - \eta\gamma^2)^2(k(\eta\delta\beta - \delta\theta^2 - \eta\gamma^2) + \eta\delta\beta(2k - \beta b(\Delta - b)))^2} \right. \\
&\left. + \frac{\beta b(\Delta - b)\left(k\left(2\delta\eta\beta - \delta\theta^2 - \eta\gamma^2\right) + \eta\delta\beta(2k - \beta b(\Delta - b))\right)\left(4k\left(3\eta\delta\beta - \delta\theta^2 - \eta\gamma^2\right) + \beta b(\Delta - b)\left(2\eta\delta\beta - \delta\theta^2 - \eta\gamma^2\right)\right)}{4(k(2\delta\eta\beta - \delta\theta^2 - \eta\gamma^2) + \eta\delta\beta(2k - \beta b(\Delta - b)))(3\eta\delta\beta - \delta\theta^2 - \eta\gamma^2)^2(k(\eta\delta\beta - \delta\theta^2 - \eta\gamma^2) + \eta\delta\beta(2k - \beta b(\Delta - b)))^2} \right) > 0,
\end{aligned}
$$

$$\pi_m^{\mathrm{TM}^*}-\pi_m^{\mathrm{RM}^*}=\frac{\delta\eta\left(2\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)(a-\beta c_m)^2}{8(3\eta\delta\beta-\delta\theta^2-\eta\gamma^2)^2}$$
$$\times\frac{\left(6\beta^2\eta^2\delta^2k^2-2k^2\left(\delta\theta^2+\eta\gamma^2\right)\left(4\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)-2\delta\beta^2k^2\eta^3\gamma^4b(\Delta-b)\left(2k\left(\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)+\eta\delta\beta(2k-\beta b(\Delta-b))\right)\right)}{(2k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))^2}$$
$$\times\frac{\left(2k^2\left(3\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)\left(7\eta\delta\beta-3\delta\theta^2-3\eta\gamma^2\right)+\eta\delta\beta^2b(\Delta-b)\left(6k\left(2\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)+\eta\delta\beta(4k-\beta b(\Delta-b))\right)\right)}{(k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))^2}>0.$$

So, we can get $\pi_m^{\mathrm{MM}^*}>\pi_m^{\mathrm{TM}^*}>\pi_m^{\mathrm{RM}^*}$. Similarly, we can verify that $\pi_t^{\mathrm{TM}^*}>\pi_t^{\mathrm{RM}^*}>\pi_t^{\mathrm{MM}^*}$, $\pi_s^{\mathrm{TM}^*}>\pi_s^{\mathrm{RM}^*}>\pi_s^{\mathrm{MM}^*}$.

(b) According to the retailer's profit in Propositions 4.1–4.3, we can get

$$\pi_r^{\mathrm{RM}^*}-\pi_r^{\mathrm{MM}^*}=k\eta\delta(a-\beta c_m)^2$$
$$\times\frac{8\beta^2\eta^2\delta^2k^2-k^2\left(\delta\theta^2+\eta\gamma^2\right)\left(4\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)-\eta\delta\beta^2b(\Delta-b)\left(2k\left(\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)+\eta\delta\beta(4k-\beta b(\Delta-b))\right)}{2(2k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))(k(2\delta\eta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))^2}>0,$$
$$\pi_r^{\mathrm{TM}^*}-\pi_r^{\mathrm{MM}^*}=\frac{\eta^3\delta^3\beta^2\left(2k^2\left(3\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)-\beta b(\Delta-b)\left(k\left(2\delta\eta\beta-\delta\theta^2-\eta\gamma^2\right)+\eta\delta\beta(2k-\beta b(\Delta-b))\right)\right)(a-\beta c_m)^2}{4(3\eta\delta\beta-\delta\theta^2-\eta\gamma^2)^2(k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))^2}$$
$$\times\frac{2k^2\left(3\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)\left(13\eta\delta\beta-2\delta\theta^2-2\eta\gamma^2\right)-\eta\delta\beta\beta^2(\Delta-b)\left(5k\left(2\delta\eta\beta-\delta\theta^2-\eta\gamma^2\right)+\eta\delta\beta(6k-\beta b(\Delta-b))\right)}{(k(2\delta\eta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))^2}>0,$$
$$\pi_r^{\mathrm{RM}^*}-\pi_r^{\mathrm{TM}^*}=\frac{\eta\delta\left(2k^3\left(\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)^2\left(3\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)^2\right)(a-\beta c_m)^2}{4(3\eta\delta\beta-\delta\theta^2-\eta\gamma^2)^2(2k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))(k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))^2}$$
$$-\frac{\begin{array}{c}\eta\delta\left(\eta\delta\beta^2b(\Delta-b)\left(2k\left(\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)+\eta\delta\beta(2k-\beta b(\Delta-b))\right)\right.\\ \left.\left(\eta^2\delta^2\beta^3b(\Delta-b)+2k\left(\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)\left(3\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)\right)\right)(a-\beta c_m)^2\end{array}}{4(3\eta\delta\beta-\delta\theta^2-\eta\gamma^2)^2(2k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))(k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))^2}.$$

We let

$$\begin{aligned}f_1(\gamma,\theta)=2k^3\left(\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)^2\left(3\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)^2-\eta\delta\beta^2b(\Delta-b)\big(2k\left(\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)\\+\eta\delta\beta(2k-\beta b(\Delta-b))\big)\times\left(\eta^2\delta^2\beta^3b(\Delta-b)+2k\left(\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)\left(3\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)\right).\end{aligned}$$

If $f_1(\gamma,\theta)\geq 0$, then $\pi_r^{\mathrm{RM}^*}\geq\pi_r^{\mathrm{TM}^*}$; if $f_1(\gamma,\theta)<0$, then $\pi_r^{\mathrm{TM}^*}>\pi_r^{\mathrm{RM}^*}$. To sum up, we can get if $f_1(\gamma,\theta)\geq 0$, $\pi_r^{\mathrm{RM}^*}\geq\pi_r^{\mathrm{TM}^*}>\pi_r^{\mathrm{MM}^*}$; if $f_1(\gamma,\theta)<0$, then $\pi_r^{\mathrm{TM}^*}>\pi_r^{\mathrm{RM}^*}>\pi_r^{\mathrm{MM}^*}$. Conclusion 5.2 is proved. □

Proof of Conclusion 5.3. According to the selling price in Propositions 4.4–4.6, we can get

$$p^{\mathrm{TR}^*}-p^{\mathrm{RR}^*}=-\delta\left(\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)(a-\beta c_m)$$
$$\times\frac{2k^2\left(\delta\beta-\gamma^2\right)\left(3\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)-\delta\beta^2b(\Delta-b)\left(k\left(3\eta\delta\beta-\delta\theta^2-2\eta\gamma^2\right)+\eta\delta\beta(k-\beta b(\Delta-b))\right)}{\begin{array}{c}2\beta\left(3\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)\left(k\left(\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)+\eta\delta\beta(2k-\beta b(\Delta-b))\right)\\ \left(k\left(3\eta\delta\beta-\delta\theta^2-2\eta\gamma^2\right)+\eta\delta\beta(k-\beta b(\Delta-b))\right)\end{array}}<0,$$
$$p^{\mathrm{MR}^*}-p^{\mathrm{RR}^*}=\frac{k^2\left(\eta\gamma^2-\delta\theta^2\right)\left(\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)(a-\beta c_m)}{\beta(k(3\eta\delta\beta-2\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(k-\beta b(\Delta-b)))(k(3\eta\delta\beta-\delta\theta^2-2\eta\gamma^2)+\eta\delta\beta(k-\beta b(\Delta-b)))}.$$

If $\eta\gamma^2-\delta\theta^2\leq 0$, that is $\frac{\gamma^2}{\delta}\leq\frac{\theta^2}{\eta}$, then $p^{\mathrm{MR}^*}\leq p^{\mathrm{RR}^*}$; if $\eta\gamma^2-\delta\theta^2>0$, that is $\frac{\gamma^2}{\delta}>\frac{\theta^2}{\eta}$, then $p^{\mathrm{RR}^*}<p^{\mathrm{MR}^*}$. To sum up, if $\frac{\gamma^2}{\delta}\leq\frac{\theta^2}{\eta}$, $p^{\mathrm{TR}^*}<p^{\mathrm{MR}^*}\leq p^{\mathrm{RR}^*}$; if $\frac{\gamma^2}{\delta}>\frac{\theta^2}{\eta}$, then $p^{\mathrm{TR}^*}<p^{\mathrm{RR}^*}<p^{\mathrm{MR}^*}$. Similarly, we can verify that if $\frac{\gamma^2}{\delta}\leq\frac{\theta^2}{\eta}$, $g^{\mathrm{TR}^*}>g^{\mathrm{MR}^*}\geq g^{\mathrm{RR}^*}$, $s_r^{\mathrm{TR}^*}>s_r^{\mathrm{MR}^*}\geq s_r^{\mathrm{RR}^*}$, $q^{\mathrm{TR}^*}>q^{\mathrm{MR}^*}\geq q^{\mathrm{RR}^*}$, $\tau_t^{\mathrm{TR}^*}>\tau_t^{\mathrm{MR}^*}\geq\tau_t^{\mathrm{RR}^*}$; if $\frac{\gamma^2}{\delta}>\frac{\theta^2}{\eta}$, then $g^{\mathrm{TR}^*}>g^{\mathrm{RR}^*}>g^{\mathrm{MR}^*}$, $s_r^{\mathrm{TR}^*}>s_r^{\mathrm{RR}^*}>s_r^{\mathrm{MR}^*}$, $q^{\mathrm{TR}^*}>q^{\mathrm{RR}^*}>q^{\mathrm{MR}^*}$, $\tau_t^{\mathrm{TR}^*}>\tau_t^{\mathrm{MR}^*}>\tau_t^{\mathrm{RR}^*}$. Conclusion 5.3 is proved. □

The proof process of Conclusion 5.4 is similar to that of Conclusion 5.2, so we will not repeat it here.

Proof of Conclusion 5.5. (a) According to the selling price in Propositions 4.1 and 4.4, we can get

$$p^{\mathrm{MR}^*}-p^{\mathrm{MM}^*} = -\frac{\delta\theta^2k^2\left(\delta\eta\beta-\delta\theta^2-\eta\gamma^2\right)(a-\beta c_m)}{\beta(k(2\delta\eta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))(k(3\eta\delta\beta-2\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(k-\beta b(\Delta-b)))}<0.$$

Similarly, we can verify that $g^{\mathrm{MR}^*}>g^{\mathrm{MM}^*}$, $s_r^{\mathrm{MR}^*}>s_m^{\mathrm{MM}^*}$, $q^{\mathrm{MR}^*}>q^{\mathrm{MM}^*}$, $\tau_t^{\mathrm{MR}^*}>\tau_t^{\mathrm{MM}^*}$.

(b) According to the manufacturer's profit in Propositions 4.1 and 4.4, we can get

$$\pi_m^{\mathrm{MR}^*}-\pi_m^{\mathrm{MM}^*} = \frac{\eta\theta^2\delta^2k^2(a-\beta c_m)^2}{2(k(2\delta\eta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))(k(3\eta\delta\beta-2\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(k-\beta b(\Delta-b)))}>0.$$

Similarly, it can be proved that $\pi_r^{\mathrm{MR}^*}>\pi_r^{\mathrm{MM}^*}$, $\pi_t^{\mathrm{MR}^*}>\pi_t^{\mathrm{MM}^*}$, $\pi_s^{\mathrm{MR}^*}>\pi_s^{\mathrm{MM}^*}$. Conclusion 5.5 is proved. □

The proving process of Conclusion 5.6 and 5.7 is similar to that of Conclusion 5.5, so we will not repeat it here.

Proof of Conclusion 5.8. (a) According to the profit of manufacturer, retailer and recycler in Proposition 4.1, we can get

$$\pi_m^{\mathrm{MM}^*}-\pi_r^{\mathrm{MM}^*} = \frac{k\eta\delta\left(k\left(\delta\eta\beta-\delta\theta^2-\eta\gamma^2\right)+\eta\delta\beta(k-\beta b(\Delta-b))\right)(a-\beta c_m)^2}{2(k(2\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))^2}>0,$$

$$\pi_r^{\mathrm{MM}^*}-\pi_t^{\mathrm{MM}^*} = \frac{k\beta\eta^2\delta^2\left(4k-\beta b^2\right)(a-\beta c_m)^2}{4(k(2\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))^2}>0.$$

So, $\pi_m^{\mathrm{MM}^*}>\pi_r^{\mathrm{MM}^*}>\pi_t^{\mathrm{MM}^*}$ is proved. Similarly, we can verify that $\pi_m^{\mathrm{MR}^*}>\pi_r^{\mathrm{MR}^*}>\pi_t^{\mathrm{MR}^*}$.

(b) According to the profit of manufacturer, retailer and recycler in Proposition 4.2, we can get

$$\pi_r^{\mathrm{RM}^*}-\pi_m^{\mathrm{RM}^*} = \frac{k\eta\delta\left(k\left(\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)+\eta\delta\beta(k-\beta b(\Delta-b))\right)(a-\beta c_m)^2}{2(2k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))^2}>0,$$

$$\pi_m^{\mathrm{RM}^*}-\pi_t^{\mathrm{RM}^*} = \frac{k\eta\delta\left(2k\left(2\eta\delta\beta-\delta\theta^2-\eta\gamma^2\right)+\eta\delta\beta^2b^2\right)(a-\beta c_m)^2}{2(2k(\eta\delta\beta-\delta\theta^2-\eta\gamma^2)+\eta\delta\beta(2k-\beta b(\Delta-b)))^2}>0.$$

So, $\pi_r^{\mathrm{RM}^*}>\pi_m^{\mathrm{RM}^*}>\pi_t^{\mathrm{RM}^*}$ is proved. Similarly, we can verify that $\pi_r^{\mathrm{RR}^*}>\pi_m^{\mathrm{RR}^*}>\pi_t^{\mathrm{RR}^*}$.

The proof of (c) is similar to (a) and (b), and is omitted. Conclusion 5.8 is proved. □

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